Tevatron 101

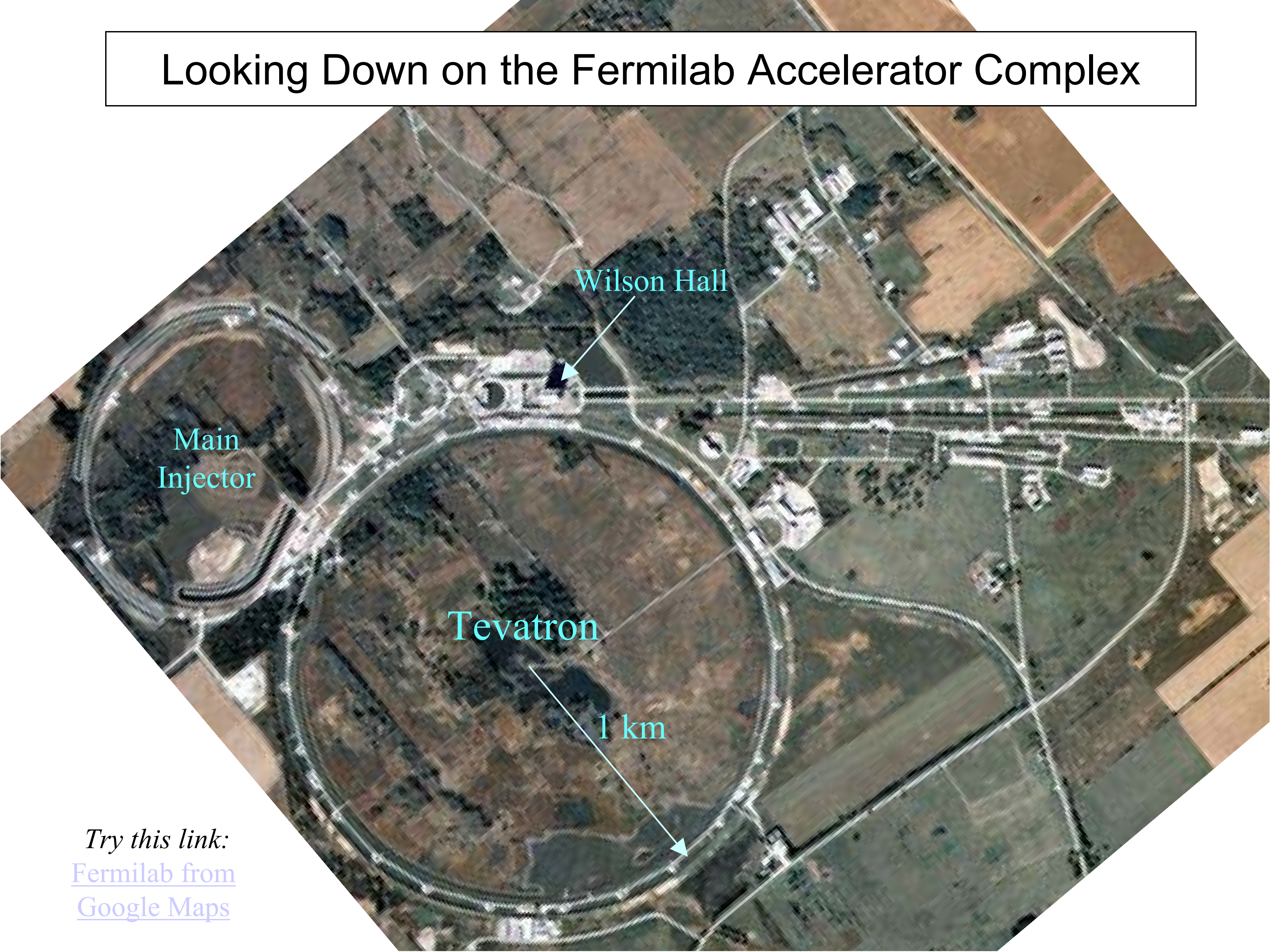
Ron Moore

Fermilab – Accelerator Division/Tevatron Dept.

A quick overview of the FNAL accelerator complex, Tevatron operations, and a few items of interest to those current and future pager carriers who worry that the CDF silicon system may look like an inviting target to the Tevatron…

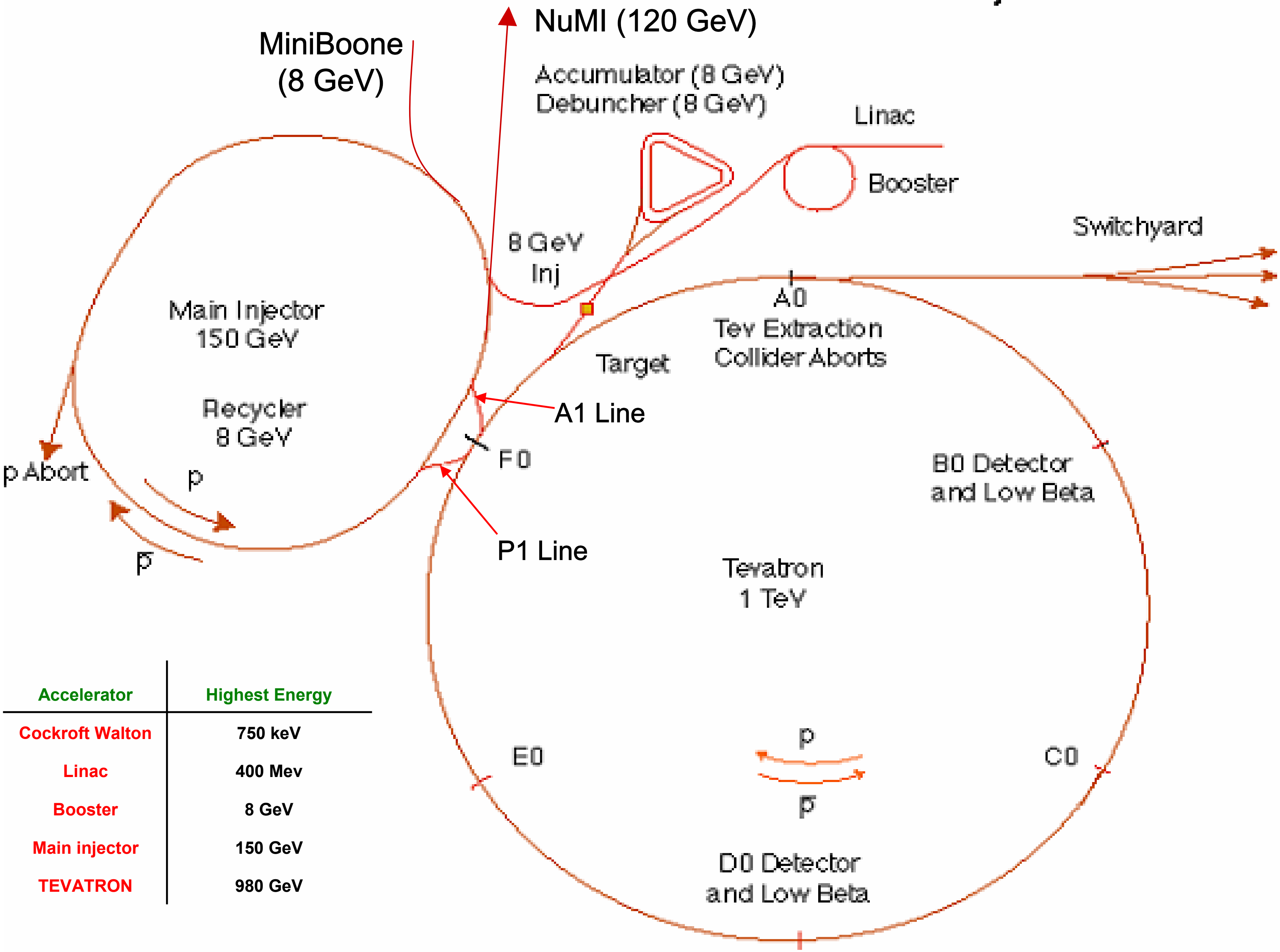
CDF Si @ UCSB - 11 May 06

Looking Down on the Fermilab Accelerator Complex



Try this link:
[Fermilab from Google Maps]

FermilabTevatron Accelerator With Main Injector

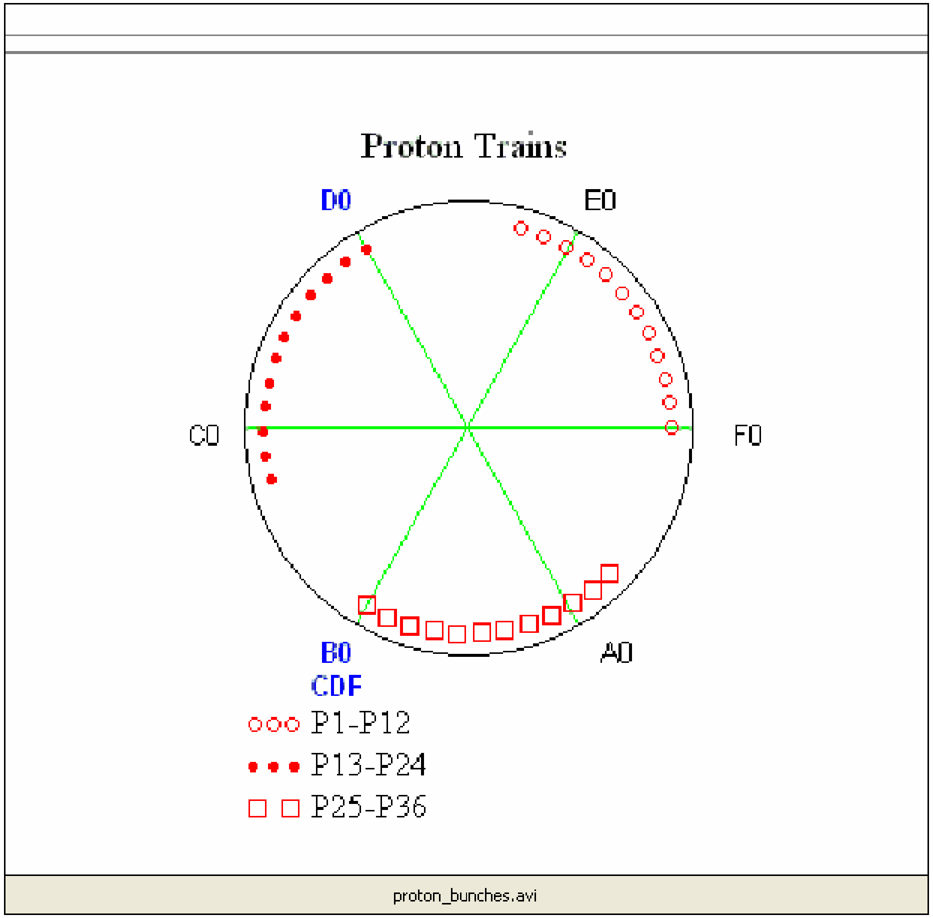


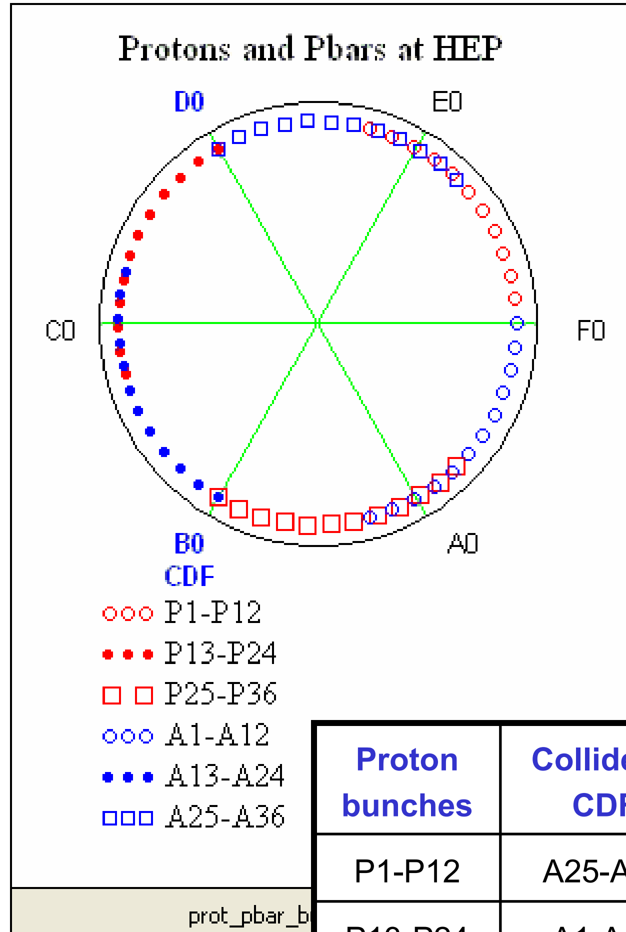
Accelerator	Highest Energy
Cockroft Walton	750 keV
Linac	400 Mev
Booster	8 GeV
Main injector	150 GeV
TEVATRON	980 GeV

Tevatron Overview

- Synchrotron providing proton-pbar collisions @ 980 GeV beam energy
- Tevatron radius = 1 km $\Rightarrow$ revolution time ~ 21 μs
- Virtually all of the Tevatron magnets are superconducting
  - Cooled by liquid helium, operate at 4 K *fun fact: ≈350 MJ stored energy!*
- 36 bunches of protons and pbars circulate in same beampipe
  - Electrostatic separators keep beams apart except where/when desired
- Injection energy is 150 GeV
  - Protons injected from P1 line at F17
  - Pbars injected from A1 line at E48
- 3 trains of 12 bunches with 396 ns separation
- 2 low β (small beam size) intersection points (CDF and D0)
- 8 RF cavities (near F0) to keep beam in bucket, acceleration
  - 1113 RF buckets (53.1 MHz $\Rightarrow$ 18.8 ns bucket length)

Bunch Positions





Proton bunches	Collide @ CDF	Collide @ D0
P1-P12	A25-A36	A13-A24
P13-P24	A1-A12	A25-A36
P25-P36	A13-A24	A1-A12

Shot Setup Overview

- MCR crew performs beam line tune-up for Pbar, Main Injector, and Tevatron
  - Verify extracted beams are injected into next machine on the desired orbit
  - Helps reduce oscillations that cause emittance (size) growth

- MCR crew also sets Tevatron tune, chromaticity, coupling to desired values @ 150 GeV
  - Important for beam lifetimes

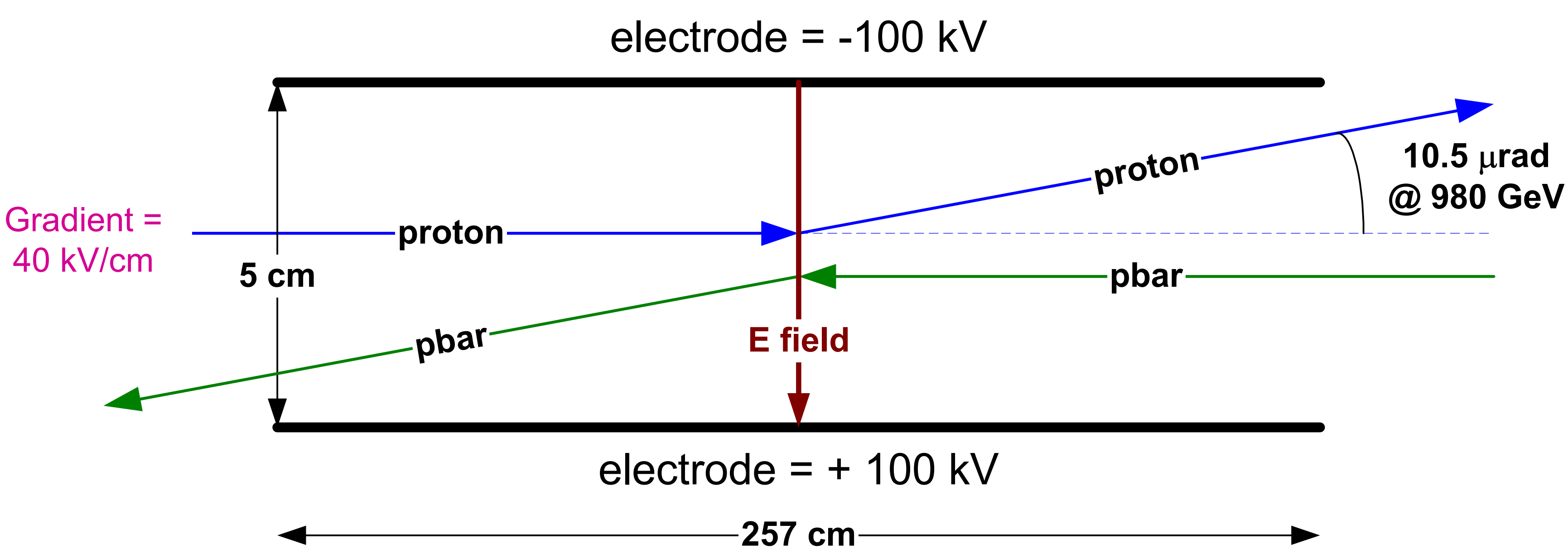
- Shots can begin once all the machine and beam-line tune-ups are complete
  - "Sequencers" handles many things automatically

Shots to the Tevatron

- Protons are injected first (onto central orbit) 1 bunch at a time
- Separators turned on to put protons on helical orbit
- Pbars are injected 4 bunches at a time into abort gaps
  - After 3rd and 6th pbar transfers, pbars "cogged" around to clear the gaps for next 3 transfers
- Accelerate beams to 980 GeV (≈90 sec)
- Final pbar "cogging" to allow collisions at CDF and D0
- Low Beta Squeeze (≈2 minutes)
- Initiate Collisions (change separator voltage around IPs)
- Scraping (~10-12 minutes)
- Turn on Tevatron Electron Lens (TEL) (knocks out beam from the abort gap)
- MCR declares store ready for HEP
- Typical time from store end to start of new store: 2-3 hours
- Once losses are low and beam is stable, ramp the HV and begin taking data

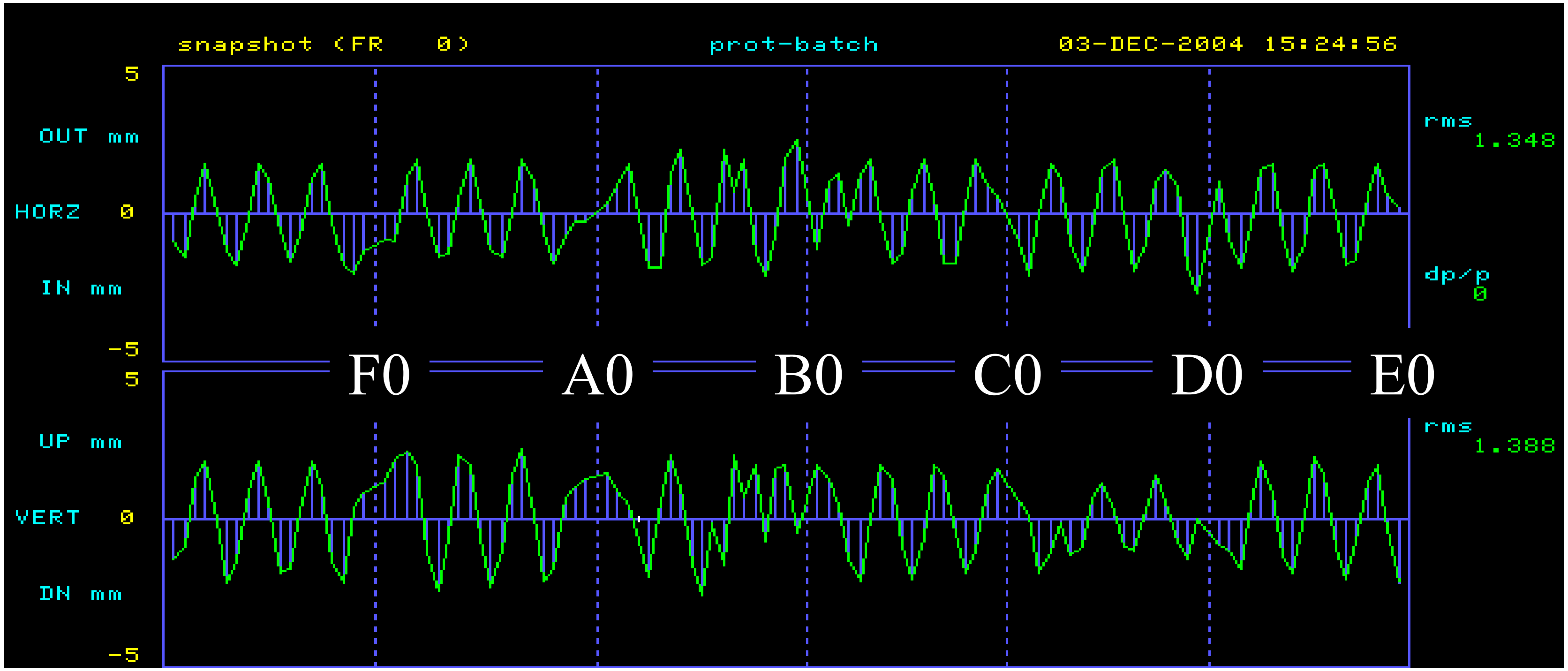
Separators

- Used to kick protons and pbars onto different helical orbits
- Electric field between parallel plate electrodes kick protons and pbars in opposite directions
  - Kick angle = # modules * (2 * Voltage / Gap) * Length / Energy



Helix

- Protons & pbars spiral around each other as they revolve in opposite directions
  - Deliberately running beams off-center by several mm
- Can control tunes, etc., of each beam (nearly) independently
- Helix size limited by physical aperture @ 150 GeV, separator voltage @ 980 GeV
  - High voltage ⇒ increased risk of spark (breakdown) between separator electrodes



Ramp

- 150 → 980 GeV in 86 sec; max ramp rate is 16 GeV/s
- Hysteretic “snapback” of magnets occurs over first several seconds
  - Complicates setting of tune, coupling, chromaticity there
- 8 RF cavities – 4 proton + 4 pbar
  - Phased such that one beam sees no net voltage from other cavities
  - RF voltage is constant; bucket area minimum early in ramp
- Bunch lengths shrink by $(980/150)^{1/4} \approx 1.6$
  - e.g., protons: 2.8 ns → 1.7 ns *(Gaussian sigma)*
- Final pbar cogging done after reaching flattop
- Beam separation decreases > 600 GeV
  - Can’t run separators hard enough
  - Separation decreases faster than beam size

Squeeze

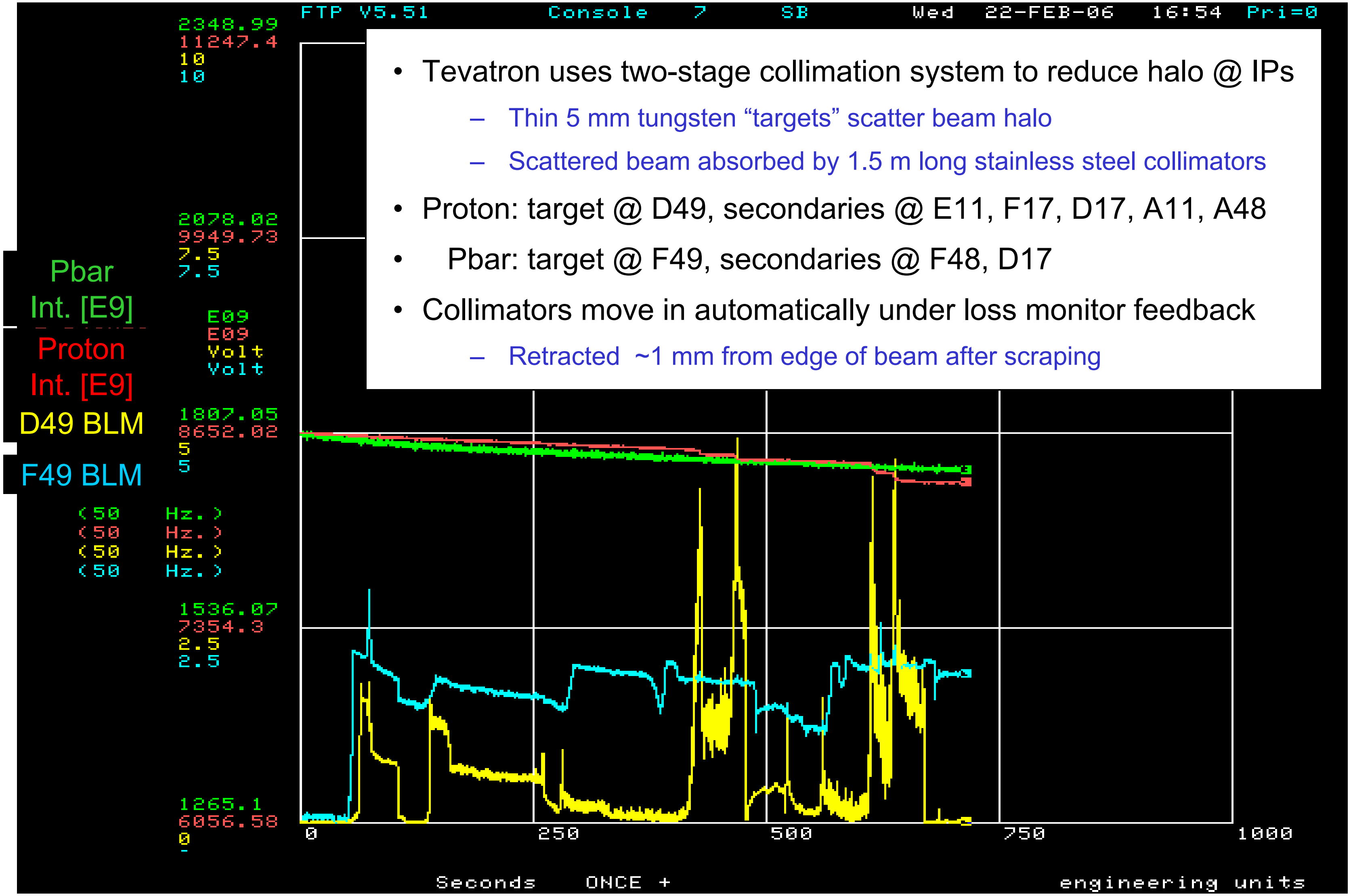
- Shrink the beams from 1.6 m → 28 cm β* at CDF and D0
  - Smaller β* means smaller beam size at the interaction points
- Takes ≈125 sec to step through 14 different lattices
- Also need to switch polarity of B17 horz separator
  - Put pbars on “right” side for diffractive physics pots during collisions
    - Injection helix → Collision helix
  - Horizontal separation minimum at that time
  - Several years ago, up to 25% pbars lost at that step
  - Developed new separator scheme to fix, but it’s still difficult to transition
- 28 cm β* implemented in September (increase luminosity ≈8%)

Initiate Collisions

- No head-on collisions until “Initiate Collisions” ramp plays out
  - Now happens automatically after the squeeze completes
  - Until then, the beams intentionally miss each other at CDF & D0
- Separator bumps removed, collisions begin
  - Ideally, orbits throughout arcs remain same, only IP changes
  - Tunes are changed, too, to compensate for beam-beam tune shifts
- Collision helix is effectively a set of separator 3 (or 4)-bumps in each plane in each arc
  - Control horz/vert separation in each arc independently
  - Can also control position (overlap) & crossing angle at IP

Halo Removal, a.k.a. Scraping

- Tevatron uses two-stage collimation system to reduce halo @ IPs
  - Thin 5 mm tungsten “targets” scatter beam halo
  - Scattered beam absorbed by 1.5 m long stainless steel collimators
- Proton: target @ D49, secondaries @ E11, F17, D17, A11, A48
- Pbar: target @ F49, secondaries @ F48, D17
- Collimators move in automatically under loss monitor feedback
  - Retracted ~1 mm from edge of beam after scraping



Luminosity Formula

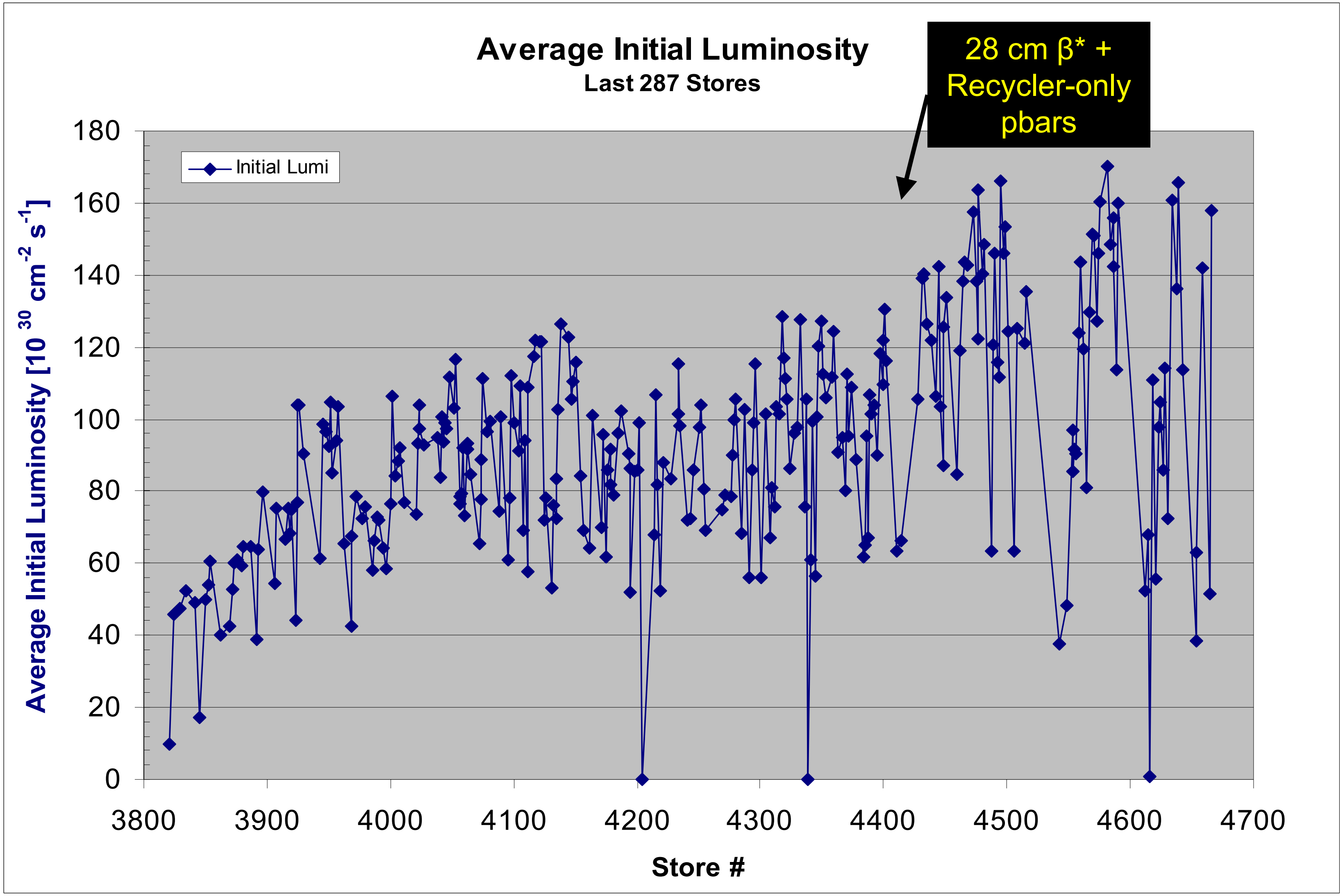
$$L = \frac{f N_p N_a}{2\pi(\varepsilon_p + \varepsilon_a)\beta^*} H\left(\sigma_z \big/ \beta^*\right)$$

- *N = bunch intensity, f = collision frequency*
- *ε = transverse emittance (size), σ_z = bunch length*
- *H = "hour glass" factor (<1, accounts for beam size over finite bunch length)*

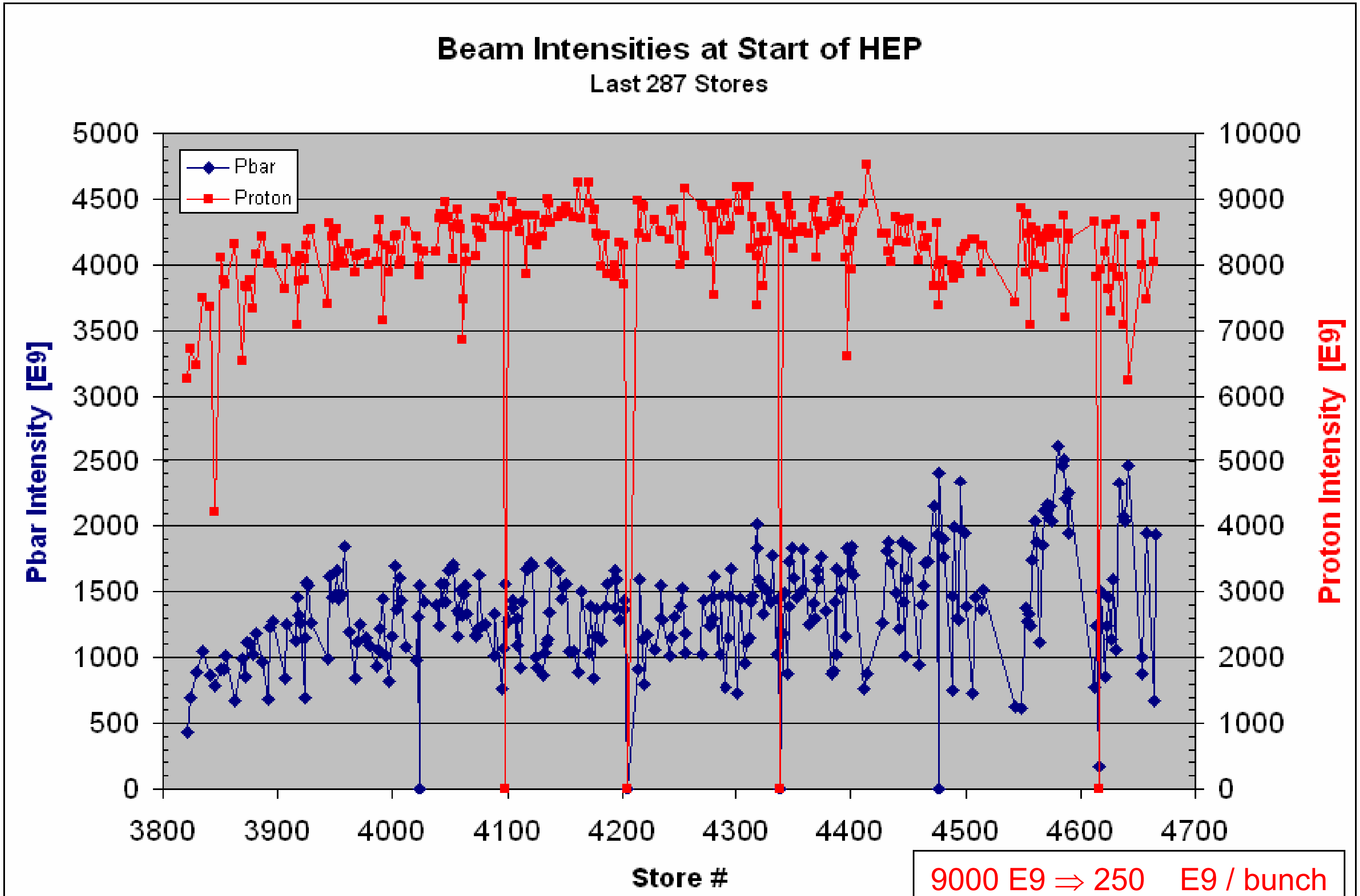
<u>Increasing the Luminosity</u>

- Smaller β^* (new 28 cm β^* lattice in Sep 05)
- Larger N_a and smaller ε_a from Recycler + electron cooling

Initial Luminosities



Beam Intensities @ HEP



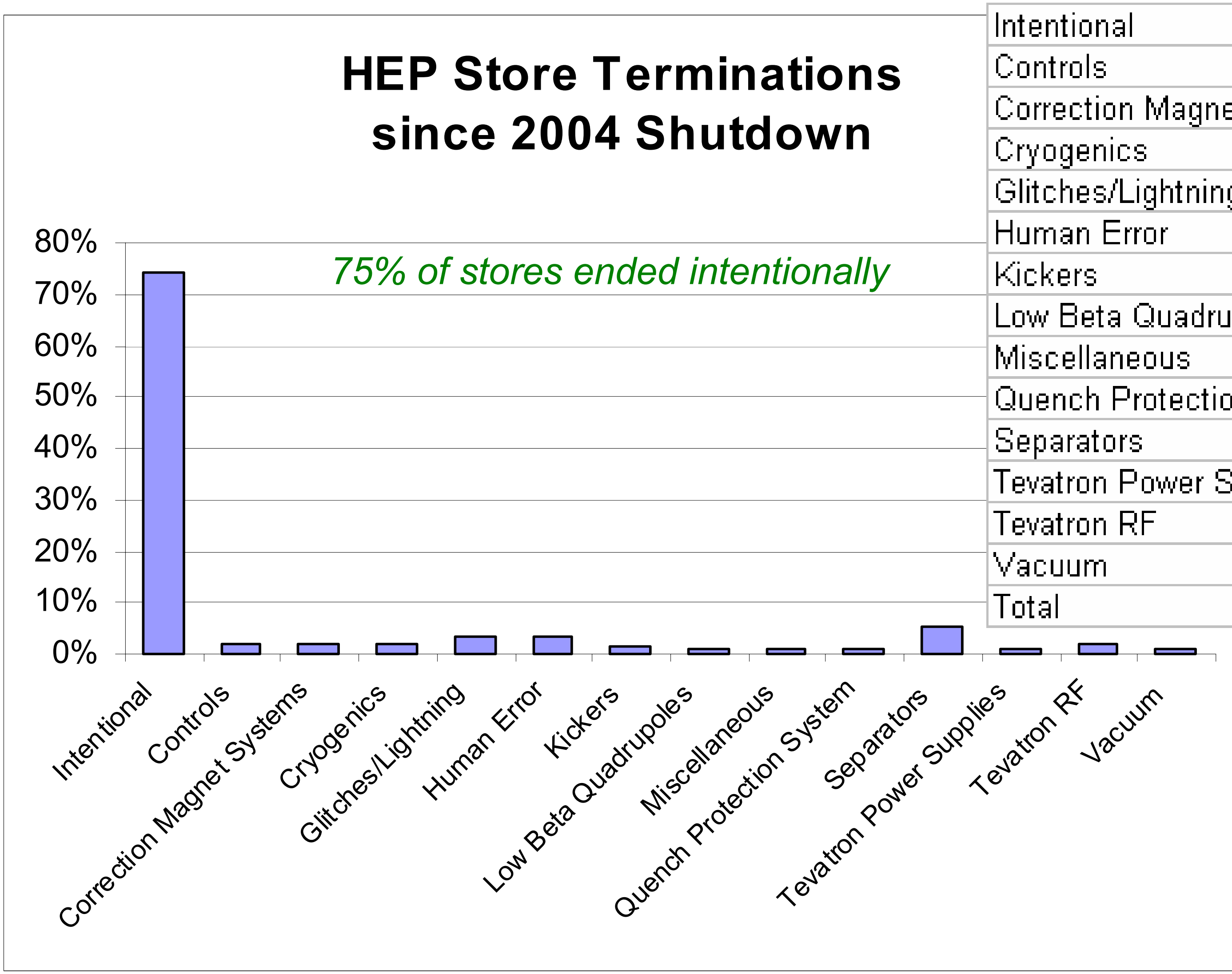
9000 E9 ⇒ 250 E9 / bunch
2250 E9 ⇒ 62.5 E9 / bunch

While the Tevatron Has a Store…

- MCR crew monitors store, responds to CDF/D0 requests
  - *e.g.* try to reduce losses - Tev expert always on-call to assist
  - Adjust pbar tunes to avoid a resonance (prevent decreases in lifetime)
  - Flying wires + orbit stabilization (automatic)

- What can go wrong? *(Too many things to list, really…)*
  - Thunderstorms, power glitches: can't control Mother Nature or Commonwealth Edison
  - Cryogenic failure, *e.g.* wet engine: usually enough time to abort beam before quench
  - Magnet power supply failure: most supply trips cause automatic abort
  - TEL trip: DC beam accumulates in abort gap
  - RF cavity trip: increase bunch lengths (decrease luminosity), dump beam into abort gap
    - Automatic abort if >1 cavity trips
  - Separator spark: drive beam into collimators causing a quench, loss of store
    - Very fast, can have bad results (indirectly)
  - Abort kicker pre-fire: 1 kicker tube fires at random time, possibly in middle of train
    - Very fast, possibly very bad $\Rightarrow$ kick protons into CDF, fry some ladders
    - 1 kicker insufficient to kick beam into abort dump, beam circulates with large oscillation

Store Termination by Category

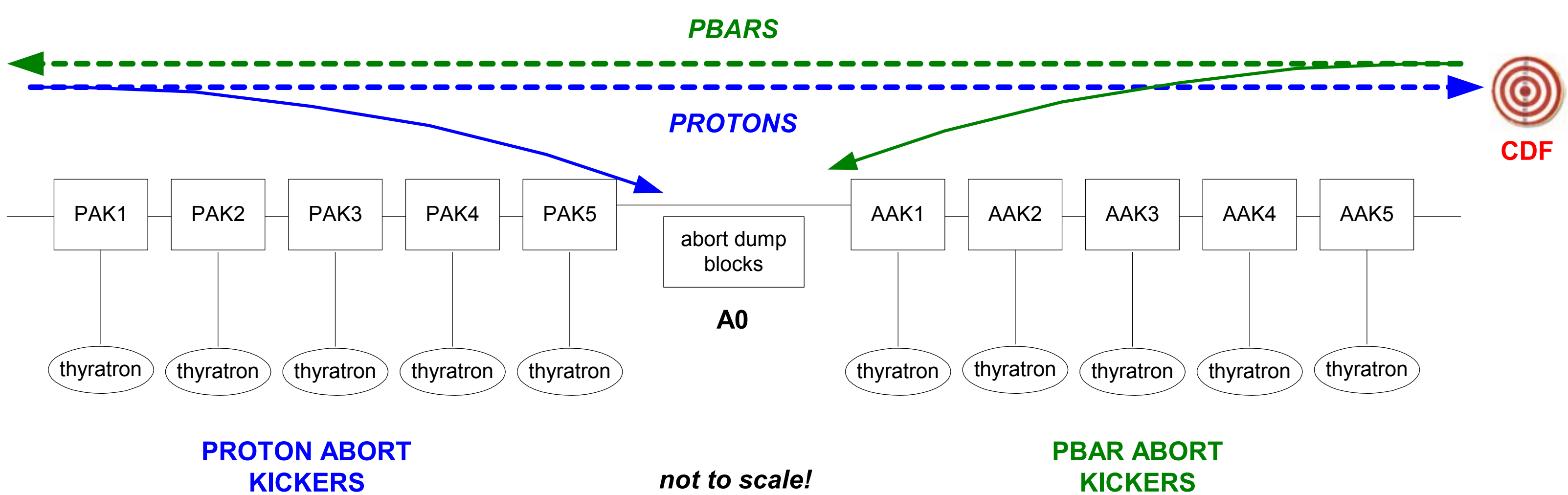


Intentional	74%
Controls	2%
Correction Magnet Systems	2%
Cryogenics	2%
Glitches/Lightning	3%
Human Error	3%
Kickers	1%
Low Beta Quadrupoles	1%
Miscellaneous	1%
Quench Protection System	1%
Separators	5%
Tevatron Power Supplies	1%
Tevatron RF	2%
Vacuum	1%
Total	100%

from J. Crawford's Operations spreadsheet

Aborting the Beam

- Abort kickers ramp up synchronously in gap between P24/P25 (A36/A1)
  - 70% full voltage when next bunch passes by; enough to kick into dump
- Beam in abort gap while kickers rising gets kicked, but not into dump
  - Can circulate with large distortion, strike apertures downstream, cause quenches, …
  - Collimators at A11, A48 help protect CDF
- Abort kicker pre-fires happen when 1 thyratron breaks down spontaneously
  - Other abort kickers automatically fire < 1 turn later to kick rest of beam into dump
  - Tubes holding off 36 kV @ 980 GeV over entire store – many hours
  - Thyratrons are conditioned at higher voltages, but pre-fires can (will) still occur



Aborting Beam Quickly

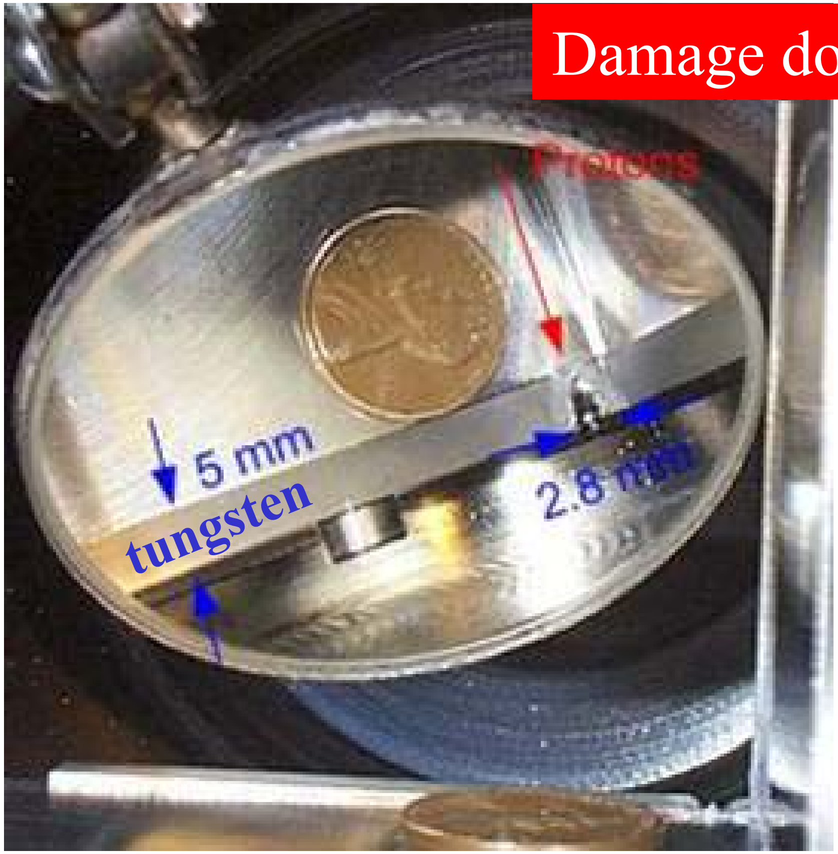
- The faster the better…why? See next slide…
- Quench Protection Monitor (QPM)
  - Prior to Dec 2003, ran on 60 Hz clock (16.7 ms)
    - Beam could circulate 100s of turns after quench
  - Modified in 2004 to "fast-abort" within 900 μs of quench
  - Tweaked after Nov 21 quench to pull abort within 550 μs
- Voltage-to-Frequency Converters (VFC)
  - Testing modification to speed measurement of resistive voltage across magnet cells
- New Beam Loss Monitor (BLM) Electronics
  - Should allow improved performance, greater flexibility
  - Being installed during shutdown

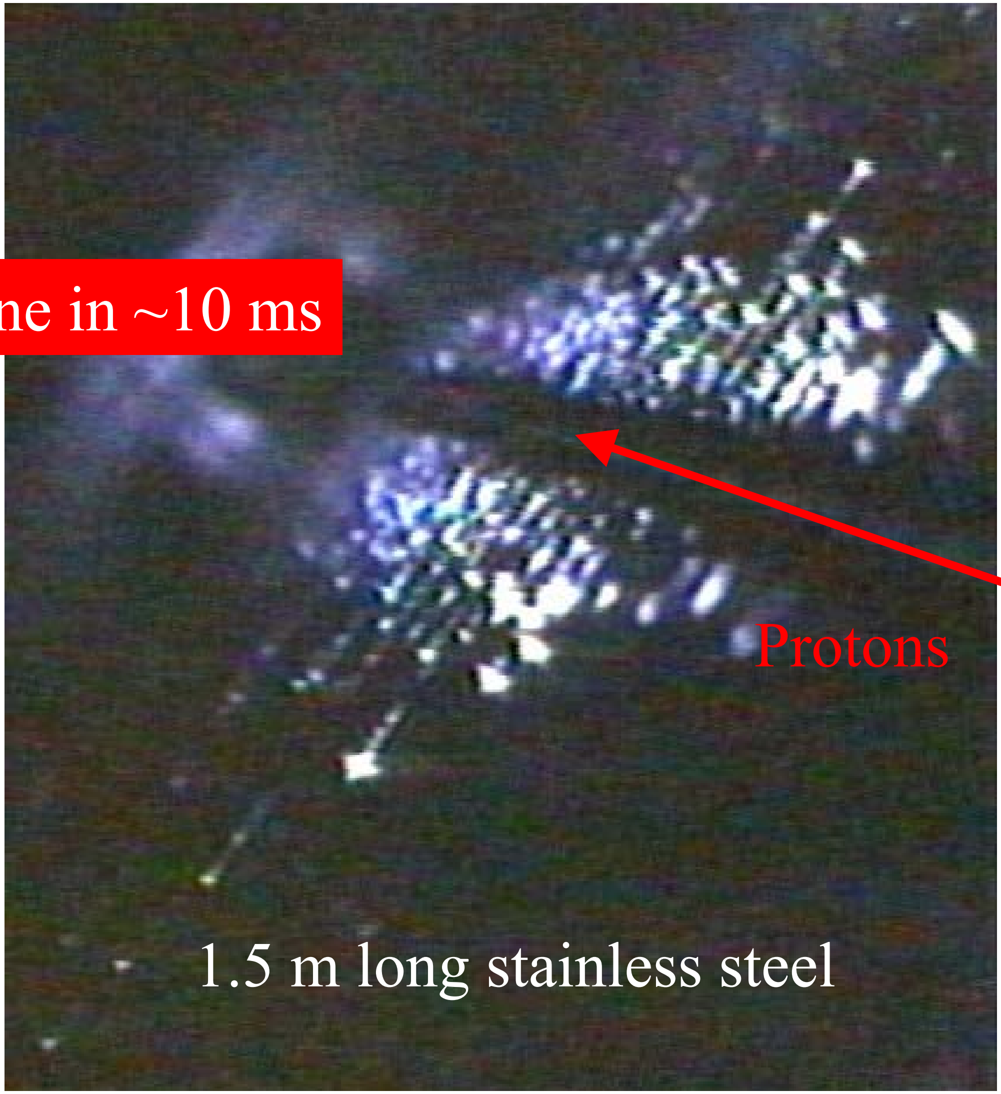
Destroyed Collimators in Tevatron

stored beam energy

10^{13} protons @ 1 TeV ≈ 1.6 MJ

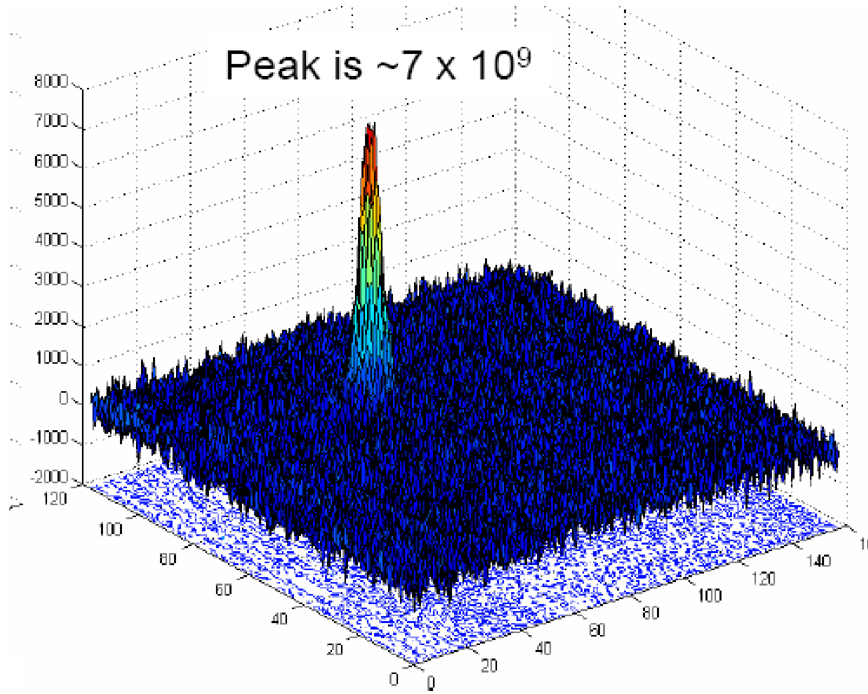
Damage done in ~10 ms





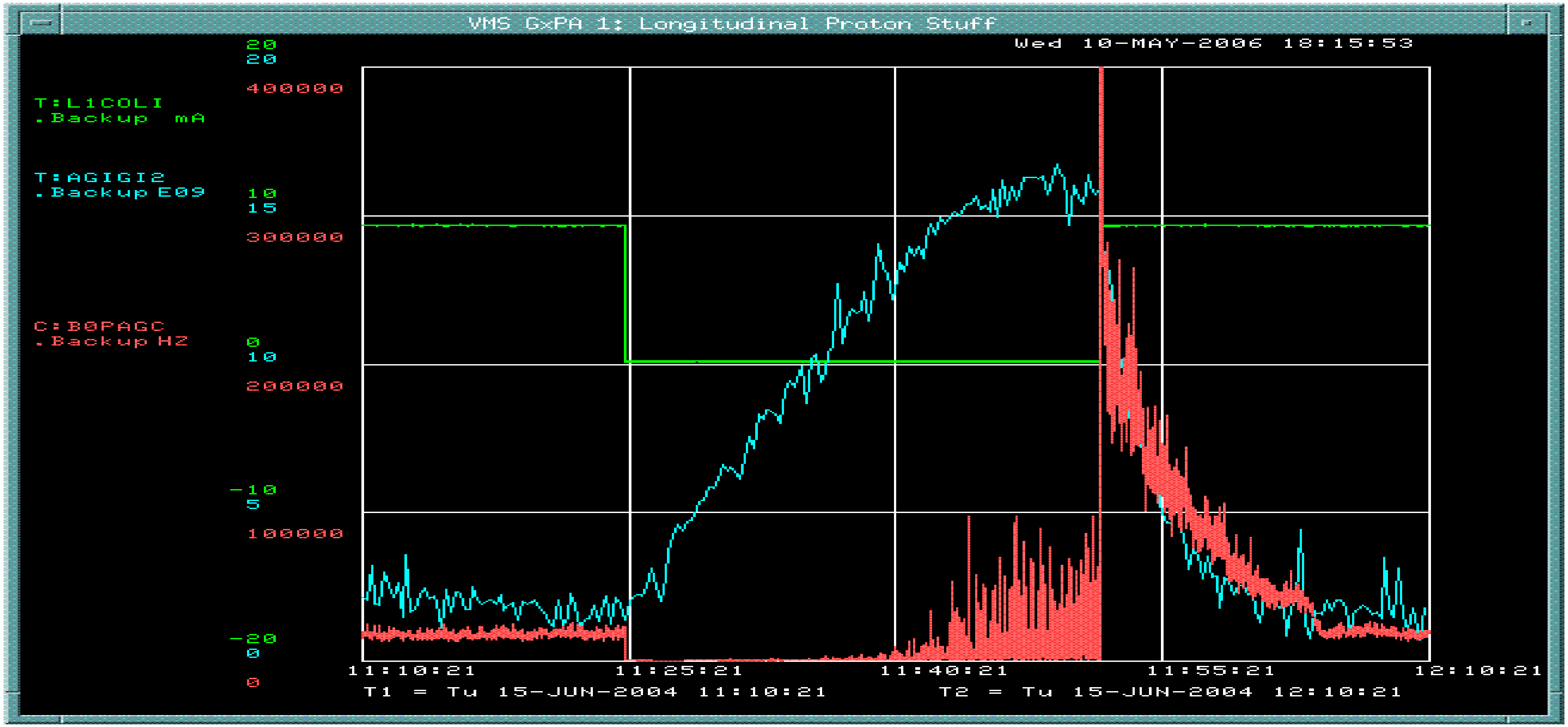
Abort Gap Monitors

- See beam in gaps directly via synchrotron light
  - Gated PMT inside synchrotron light box in C-sector
  - Can see few E9 intensity (enough to cause quenches)
  - T:AGIGI2 is important ACNET device
- Rick's counters outside of shield wall
  - Sees beam being lost from gaps ending up near CDF
  - Indirectly estimate amount of beam in gaps
  - Can vary even if intensity in gap remains constant
  - C:B0PAGC is relevant ACNET device
- We (MCR, Tev) use T:AGIGI2 to determine "safe" level of DC beam
  - 7 E9 is agreed upon "safe" limit during HEP
  - Have aborted cleanly with T:AGIGI2 = 45 E9 during HEP (beam on helix, collimators in)



TEL – Tevatron Electron Lens

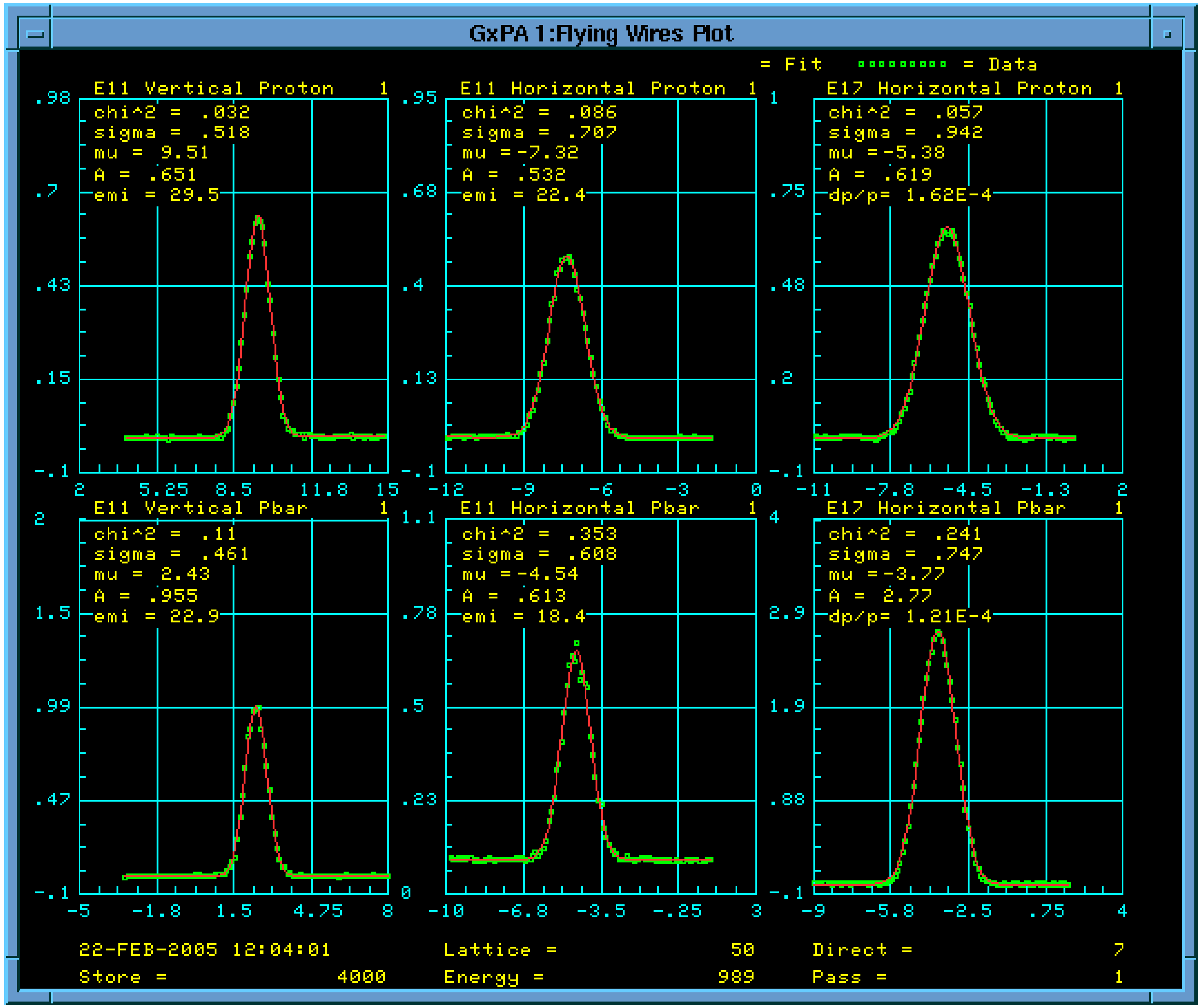
- Used continuously to remove DC beam from the gaps
- Periodic pulsing of e-beam drives beam toward tune resonances
  - Eventually lost on collimators (most of it anyway)



Flying Wires

- Fly wires through beams
- Scatted particles detected in scintillator paddles
- Can cause loss spikes in CDF/D0
- Measure transverse beam profiles

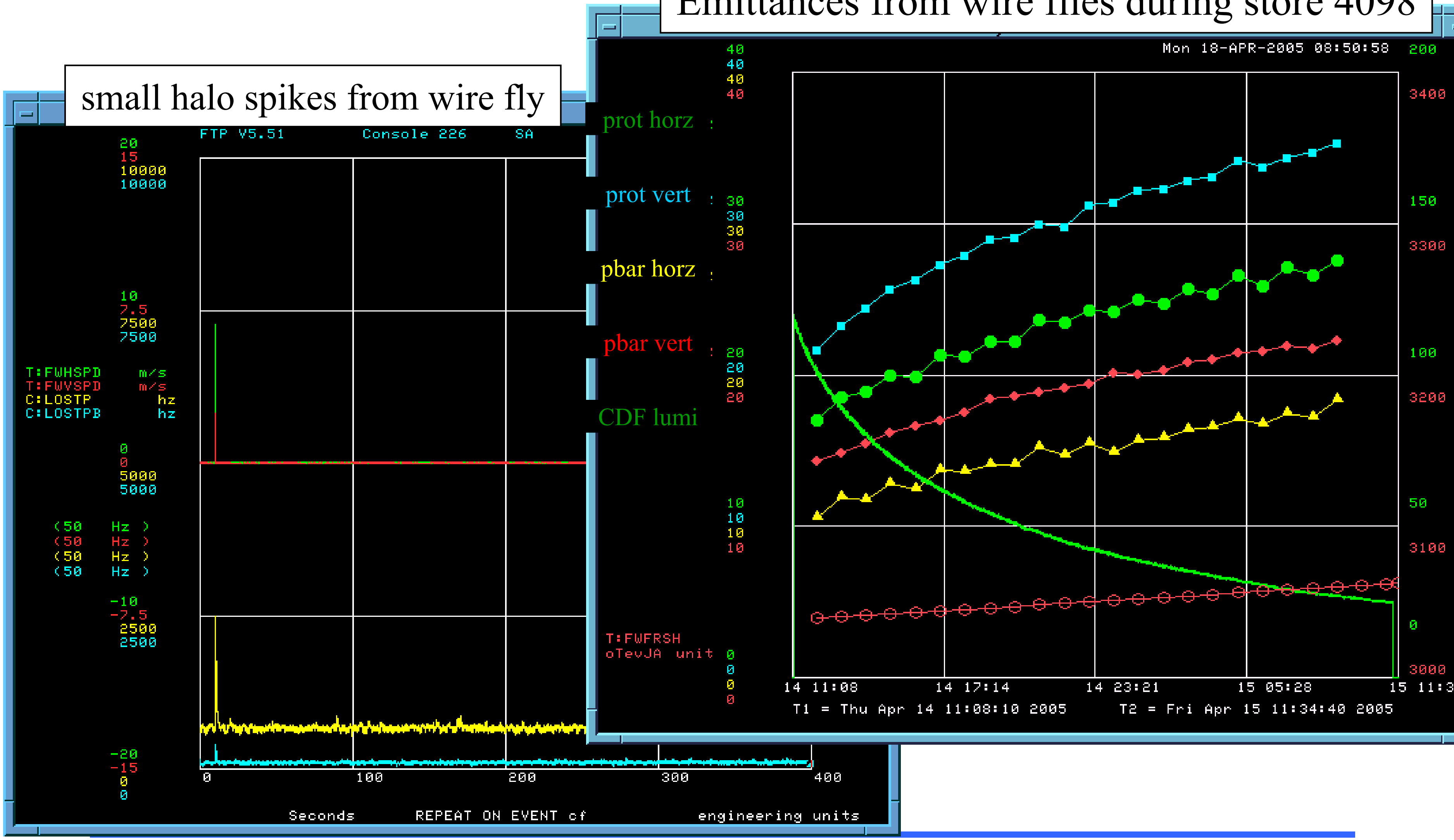
- New wires are <u>thinner</u> (7 μm), cause less loss
- Fly every hour during HEP to see emittance evolution



Flying Wires (2)

small halo spikes from wire fly

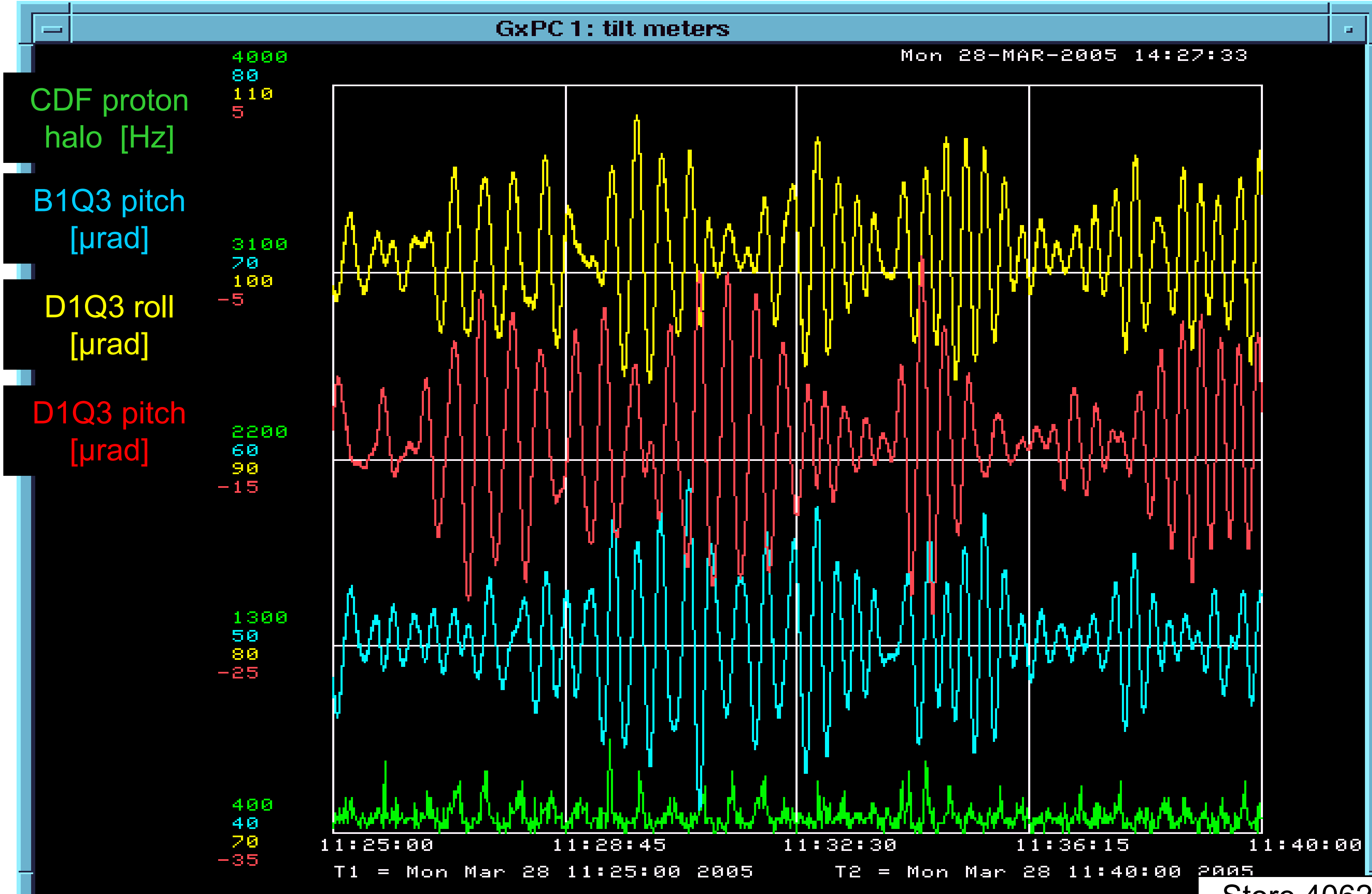
Emittances from wire flies during store 4098



Magnet Motion

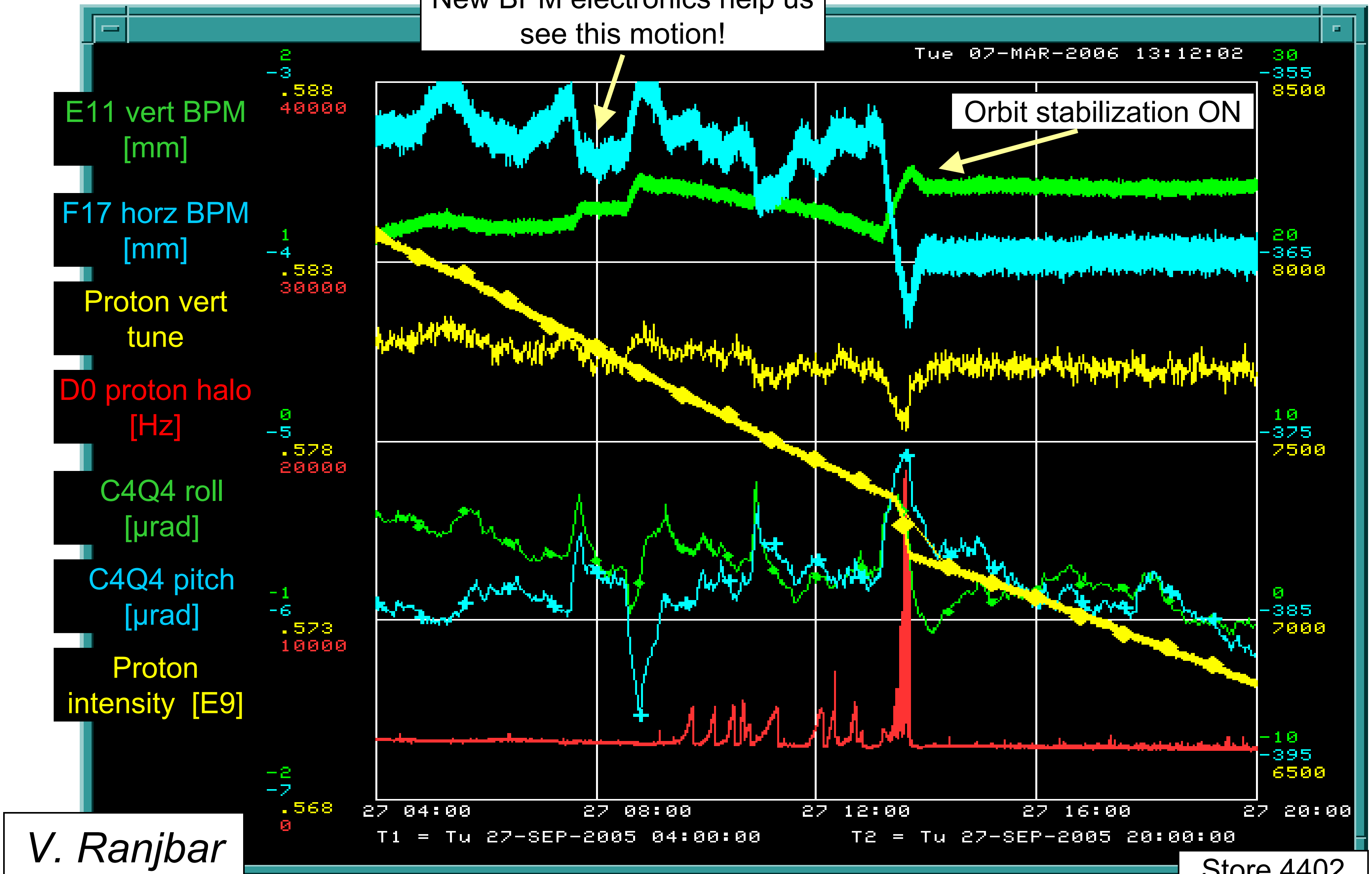
- How do see magnet motion?
  - Tiltmeters, LVDTs, water levels, surveys
- Observed magnet motion on different time scales
  - Slow drift over weeks, months
    - Ground motion, etc.
  - Wiggles, jumps over seconds, minutes, hours
    - Quenches, earthquakes, HVAC, weather, tides
  - Vibrations at few → tens of Hz
    - Traffic, pumps
- ~μm magnet motion near IPs give ~mm orbit changes in arcs
  - Readily observable during stores using Beam Position Monitors (BPMs)
  - Can cause spikes in background

Sumatra Earthquake 3/28/05



Store 4062

Magnet Motion / Orbit Stabilization



The Future

- Get to initial luminosities $L = 300\ 10^{30}\ cm^{-2}\ s^{-1}$
- Want 2× more pbars!
- New working point? Near 1/2 or 2/3?
  - Simulations show better lifetime
  - More tune space may allow 20% more protons?
- 4 more years?!
  - Accelerator upgrades nearly complete…keep complex running well

- ***Maximize <u>integrated</u> luminosity recorded to tape by CDF & D0***

Additional Slides

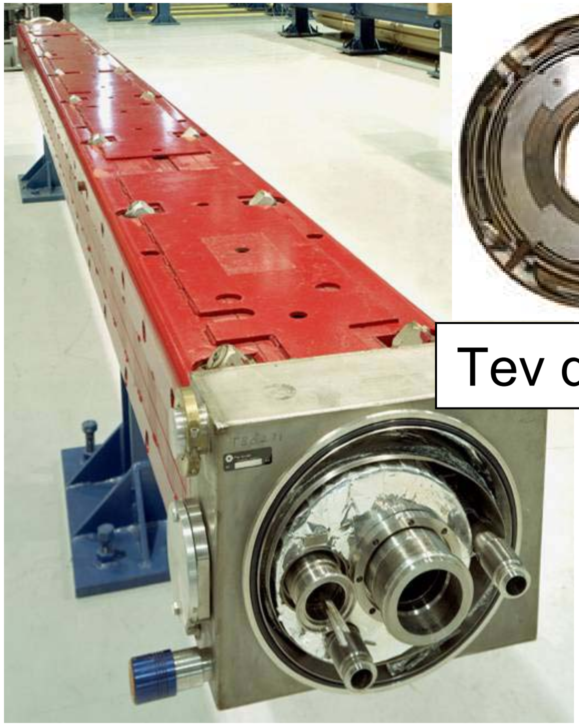
Glossary

- **Stack** = antiprotons being stored in the Accumulator
- **Stash** = antiprotons being stored in the Recycler
- **Store** = beam kept circulating continuously in the Tevatron; can be an HEP store (protons and pbars), or proton-only for studies/maintenance
- **Ramp** = accelerating beam from 150 GeV to 980 GeV (in Tev), dipole magnet current increasing to bend beam harder as energy rises
- **Flattop** = Tev ramped to 980 GeV, **before** low β squeeze
- **Squeeze** = Focusing the beams to smaller transverse size at CDF/D0
- **Low Beta** = Tev @ 980 GeV, **after** low β squeeze
- **Initiate Collisions** = turn on electrostatic separators that make beams collide at the centers of CDF and D0
- **Scraping** = Removal of beam “halo” (stuff far away from beam center) by moving stainless steel collimators close to beam; reduces beam losses at CDF/D0; done automatically after collisions begin; takes 12-15 minutes
- **Cogging** = moving the (pbar) beam longitudinally desired location
- **Abort Gap** = series of empty buckets between bunch trains to allow abort kickers to reach proper voltage to kick beam into dump blocks

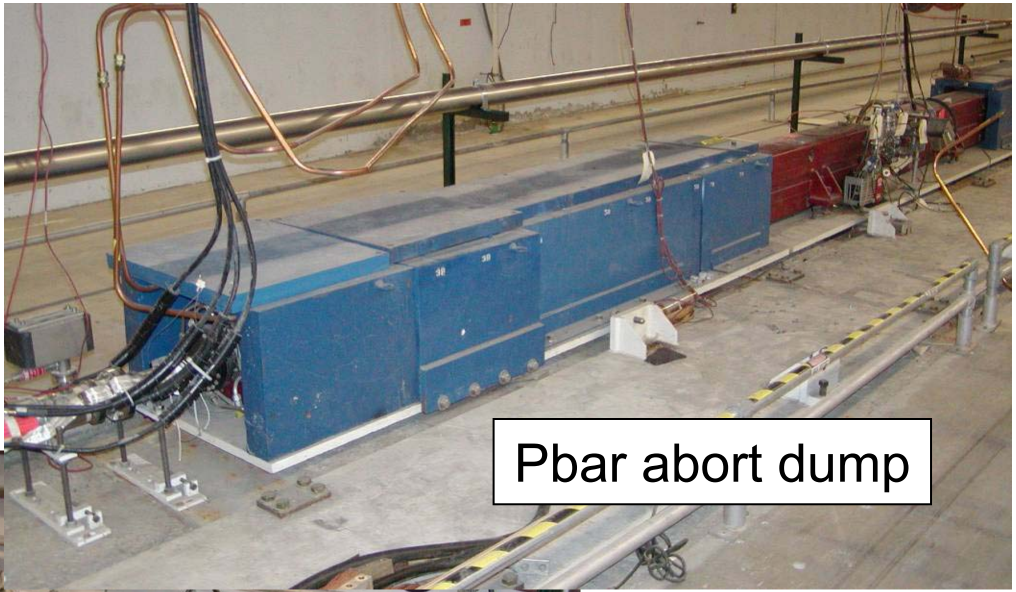
Glossary

- **BLM** = Beam Loss Monitor
  - Ionization chambers that measure dose rates (beam losses) at many positions around the ring.
- **BPM** = Beam Position Monitor
  - Measures horz or vert beam positions within beampipe (≈10 μm resolution)
  - Pick-ups located near each quadrupole (≈240 BPMs)
- **FBI** = Fast Bunch Integrator
  - Provides Tev bunch intensity measurements
- **SBD** = Sampled Bunch Display
  - Gives Tev bunch length and intensity measurements
- **DC Beam** = beam not captured in an RF bucket
  - Can circulate around for minutes before losing energy via synchrotron radiation and striking an aperture (collimator)
- **TEL** = Tevatron Electron Lens
  - Device that shoots a ~few mA electron beam in the Tev beam pipe
  - Used to knock beam out of the abort gaps (reducing CDF backgrounds)
  - Intended to compensate beam-beam tune shift of pbars from protons (not yet)
- **QPM** = Quench Protection Monitor
- **QBS** = Quench Bypass Switch

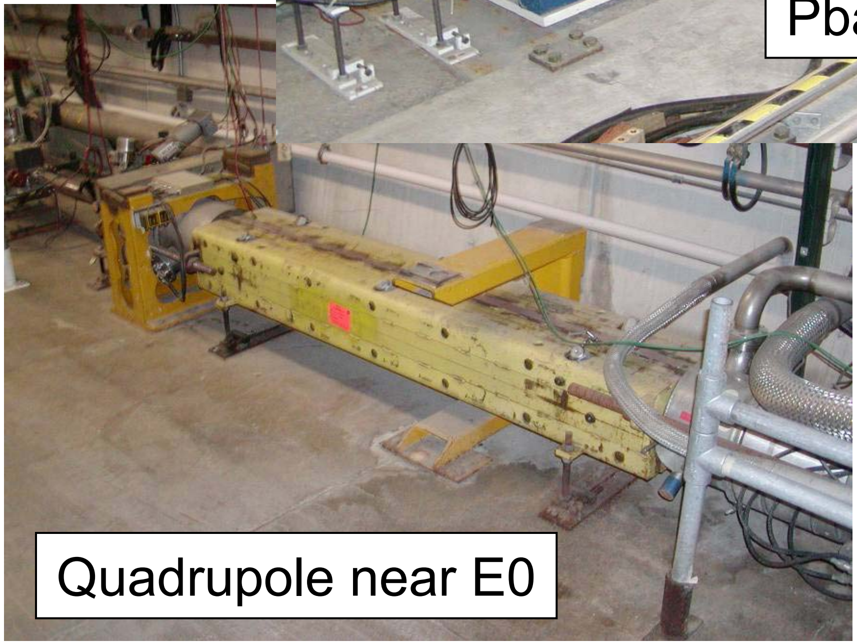
Pictures of Magnets, etc.



Tev dipole



Pbar abort dump

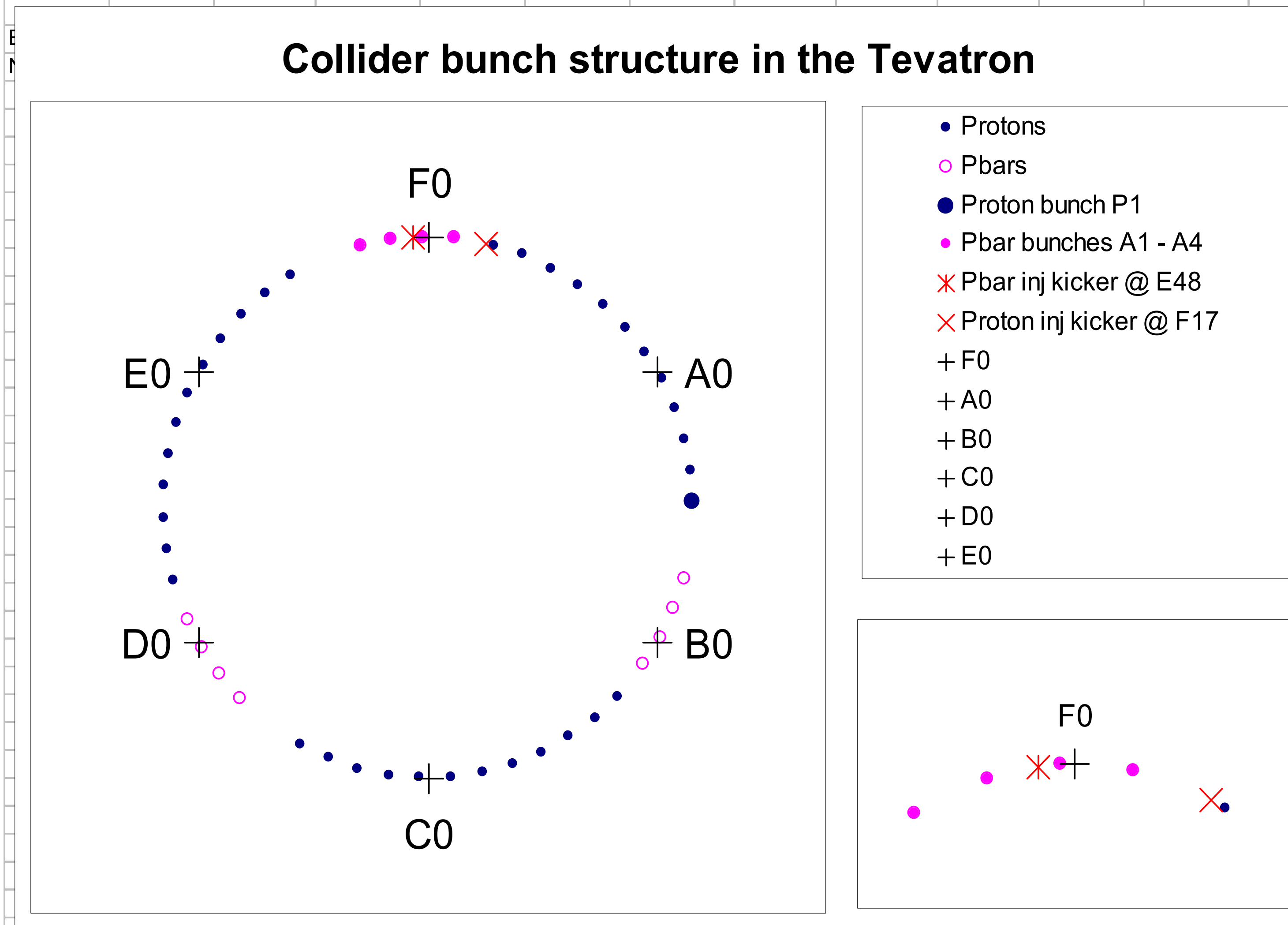


Quadrupole near E0

Demonstration of Pbar Cogging in the Tevatron

Injection cogging for Pbar bunches 1-4, 13-16, and 25-28 is at -161 RF buckets
Injection cogging for Pbar bunches 5-8, 17-20, and 29-32 is at -77 RF buckets
Injection cogging for Pbar bunches 9-12, 21-24, and 33-36 is at +7 RF buckets

Time (in RF buckets)	275
Cogging (in RF buckets)	-161



24	602	327	556	-1.846003	3.13877	-0.962369	-0.271746	0.002823

Table of Separator Stations

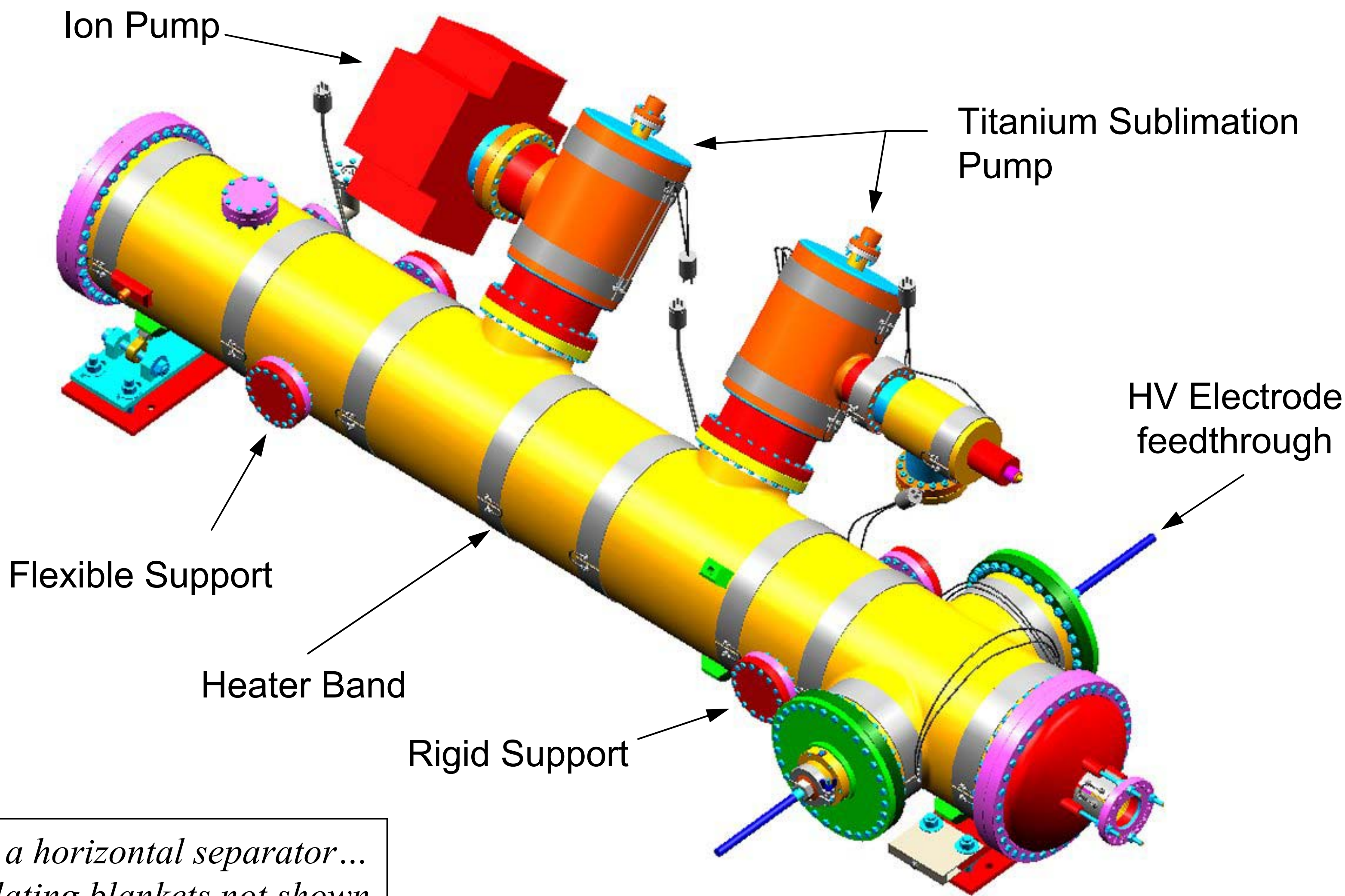
Horizontal	# modules		Vertical	# modules
B11	2	short arc	B11	1
B17	4		B48	1
			C17	4
C49	1		C49	2
D11	2	long arc	D11	1
D48	1		D17	2
A17	1		A17	1
A49	1		A49	2

New separators being installed in the current shutdown

Total: 26 separator modules + 4 spares

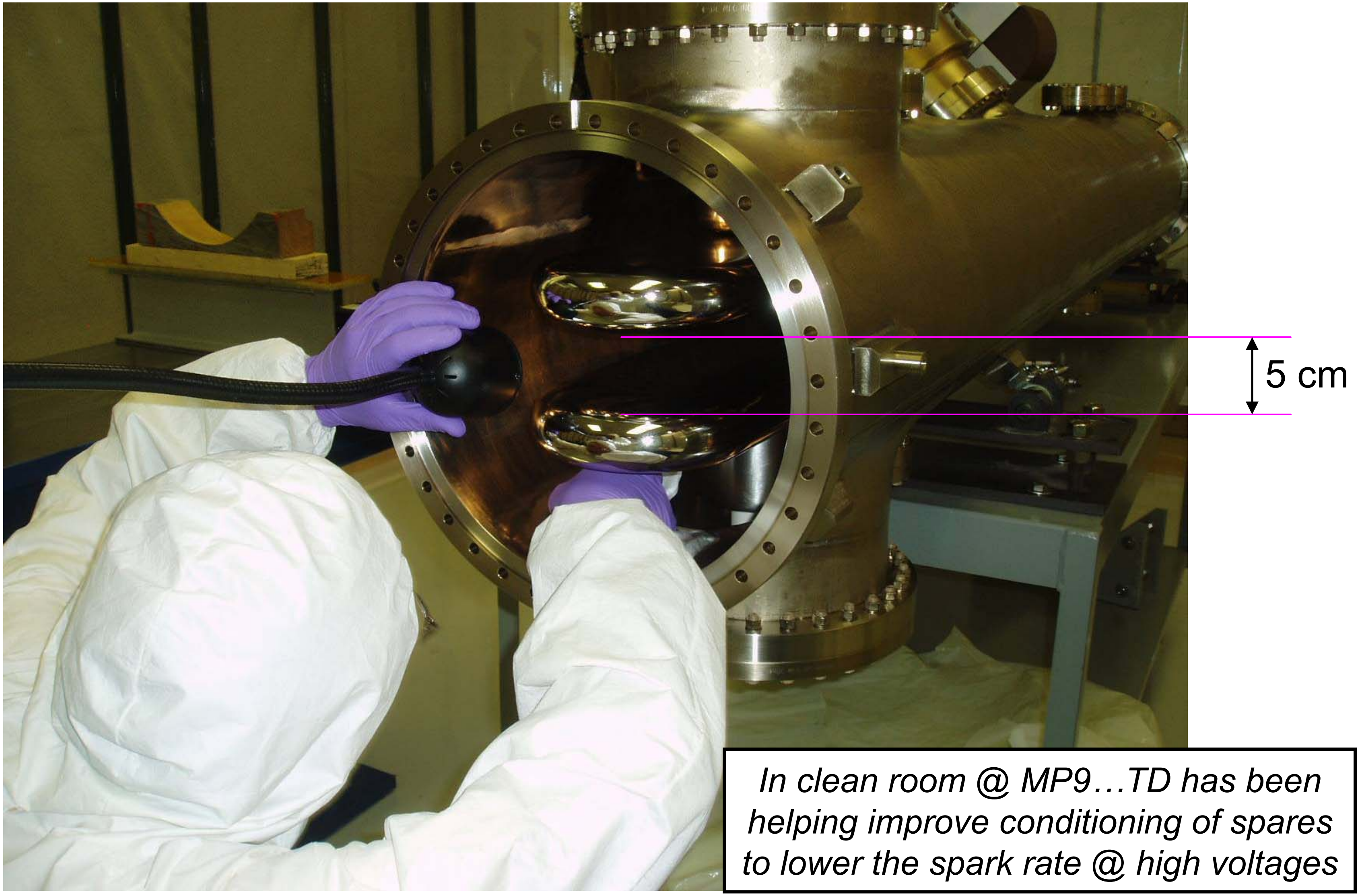
Each separator station has 2 power supplies, polarity switch, resistors, controls…

Tevatron Electrostatic Separator Components



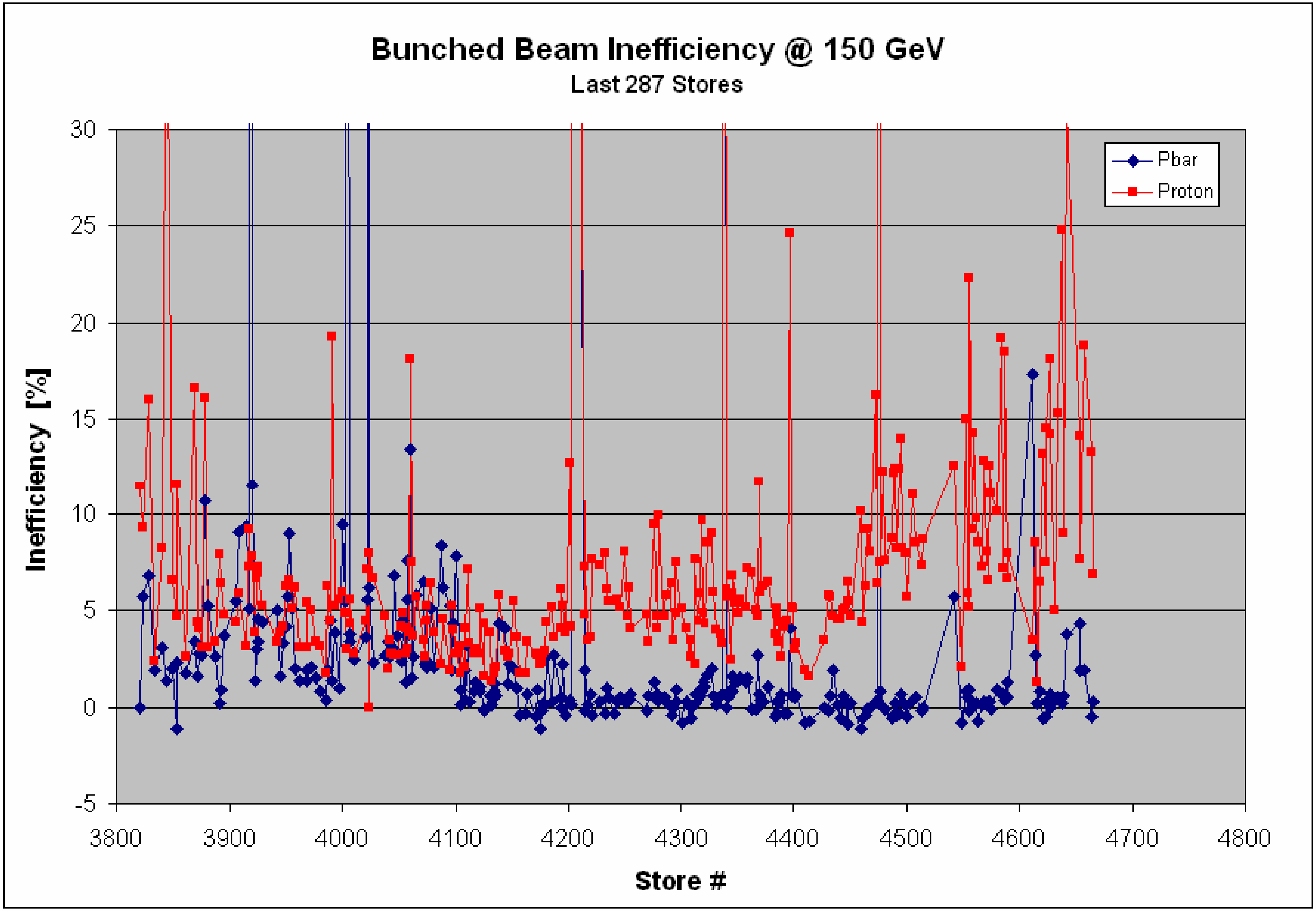
This is a horizontal separator…
…insulating blankets not shown

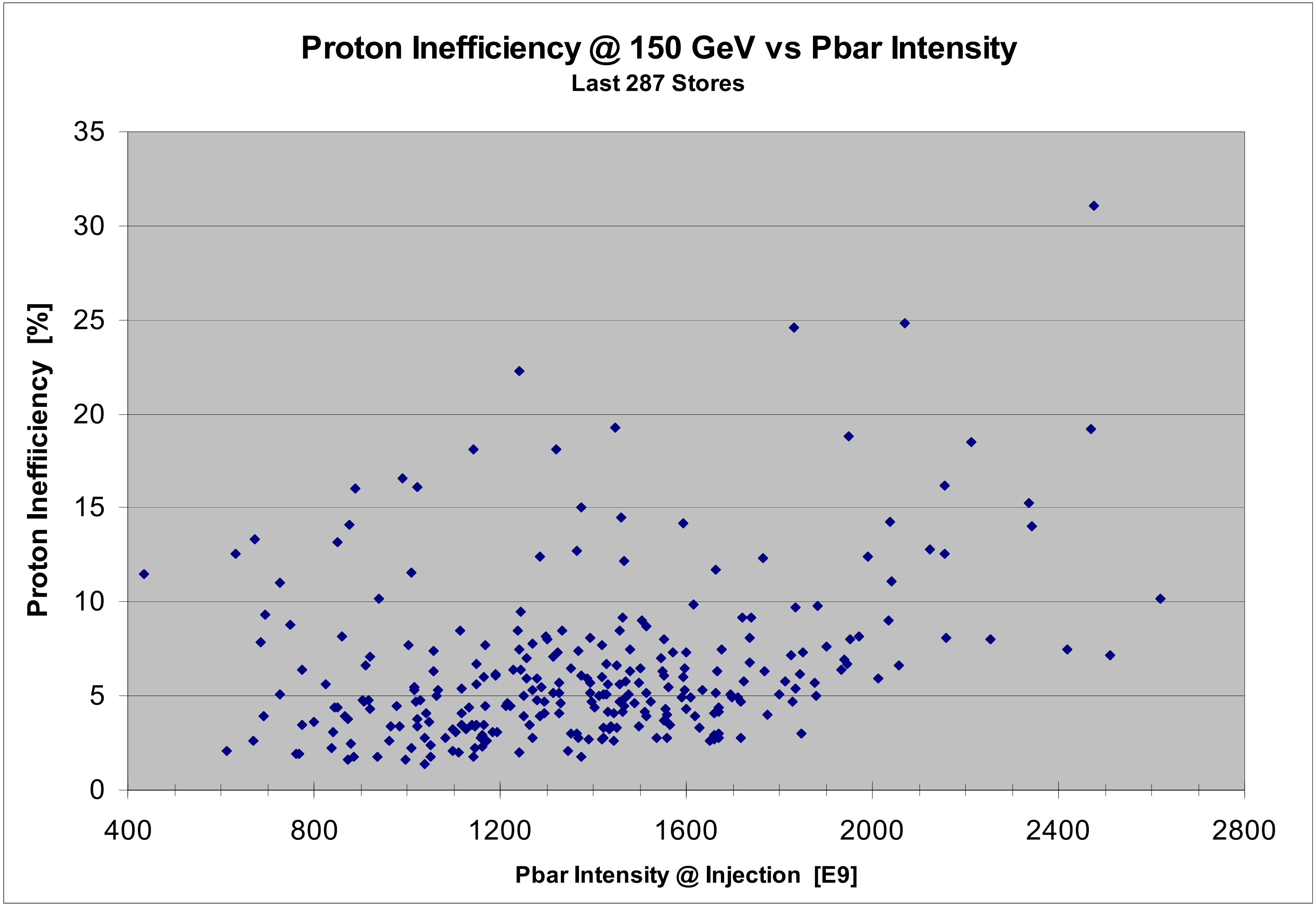
Looking into a separator



In clean room @ MP9…TD has been helping improve conditioning of spares to lower the spark rate @ high voltages

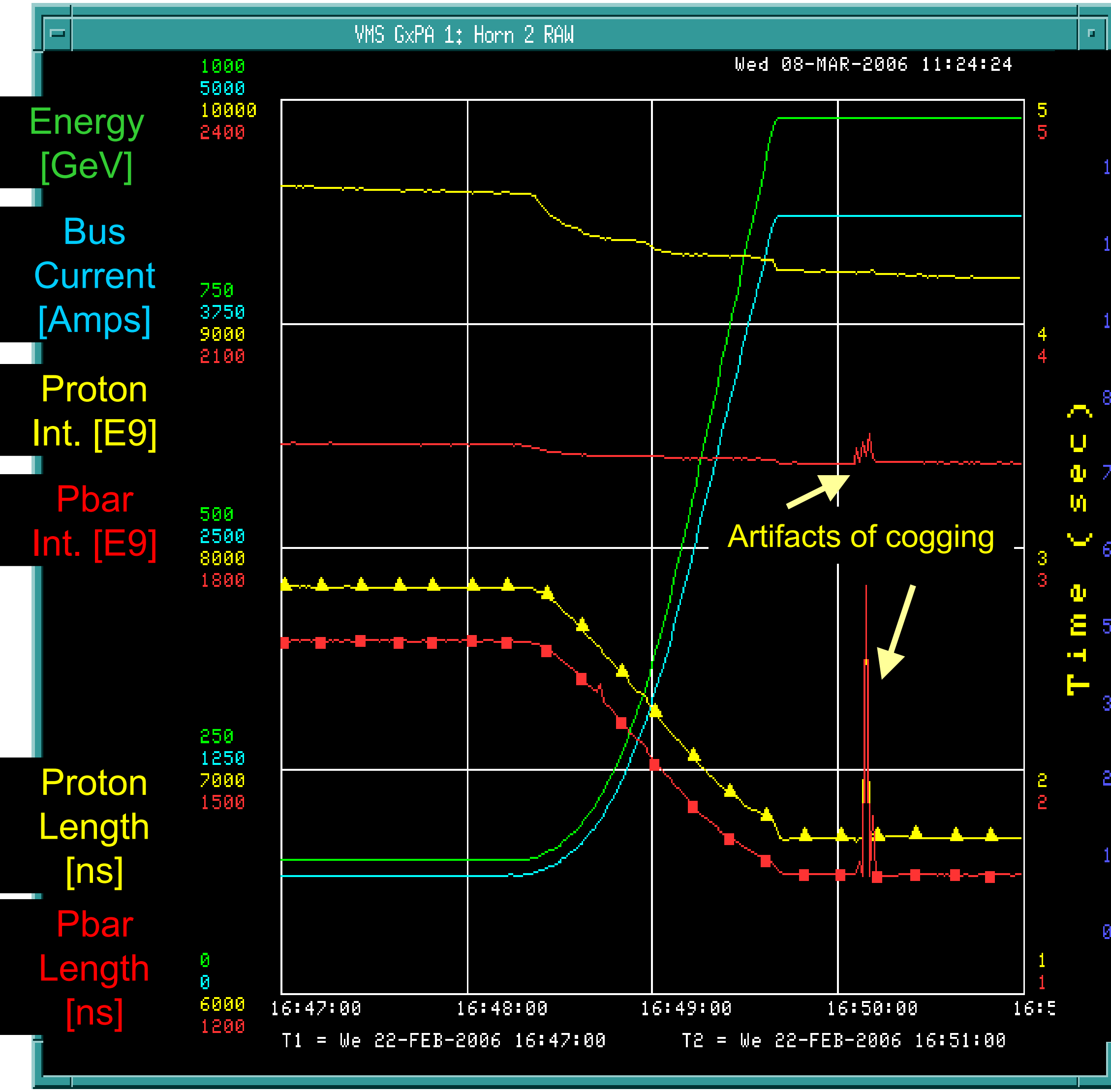
Inefficiencies @ 150 GeV

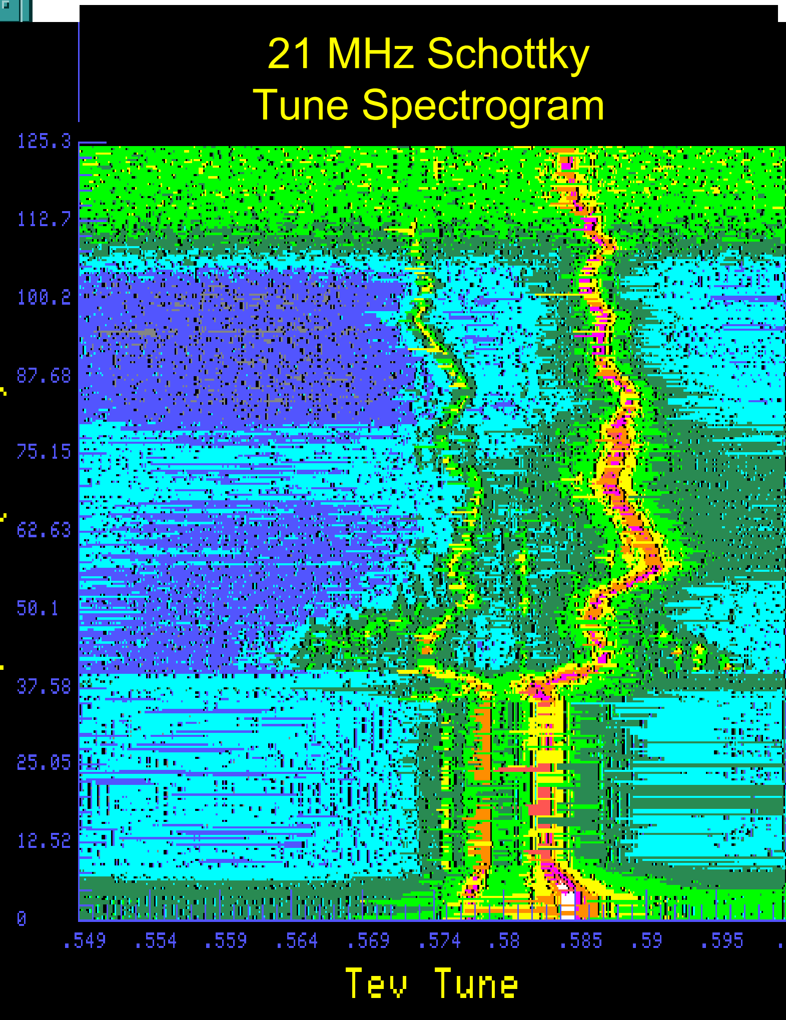




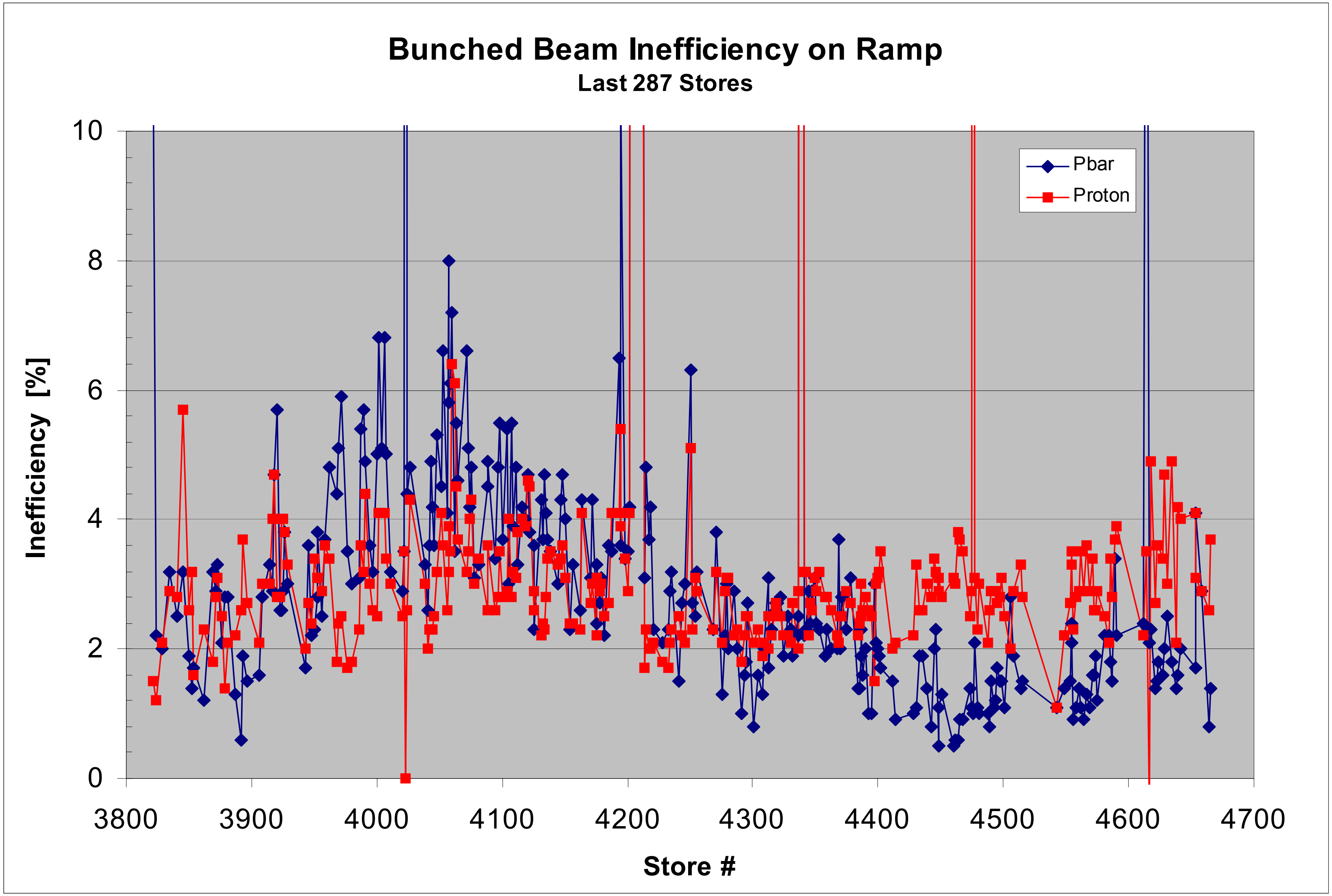
Proton Inefficiency @ 150 GeV vs Pbar Intensity
Last 287 Stores
Proton Inefficiency [%]
35
30
25
20
15
10
5
0
400
800
1200
1600
2000
2400
2800
Pbar Intensity @ Injection [E9]

Up the Ramp

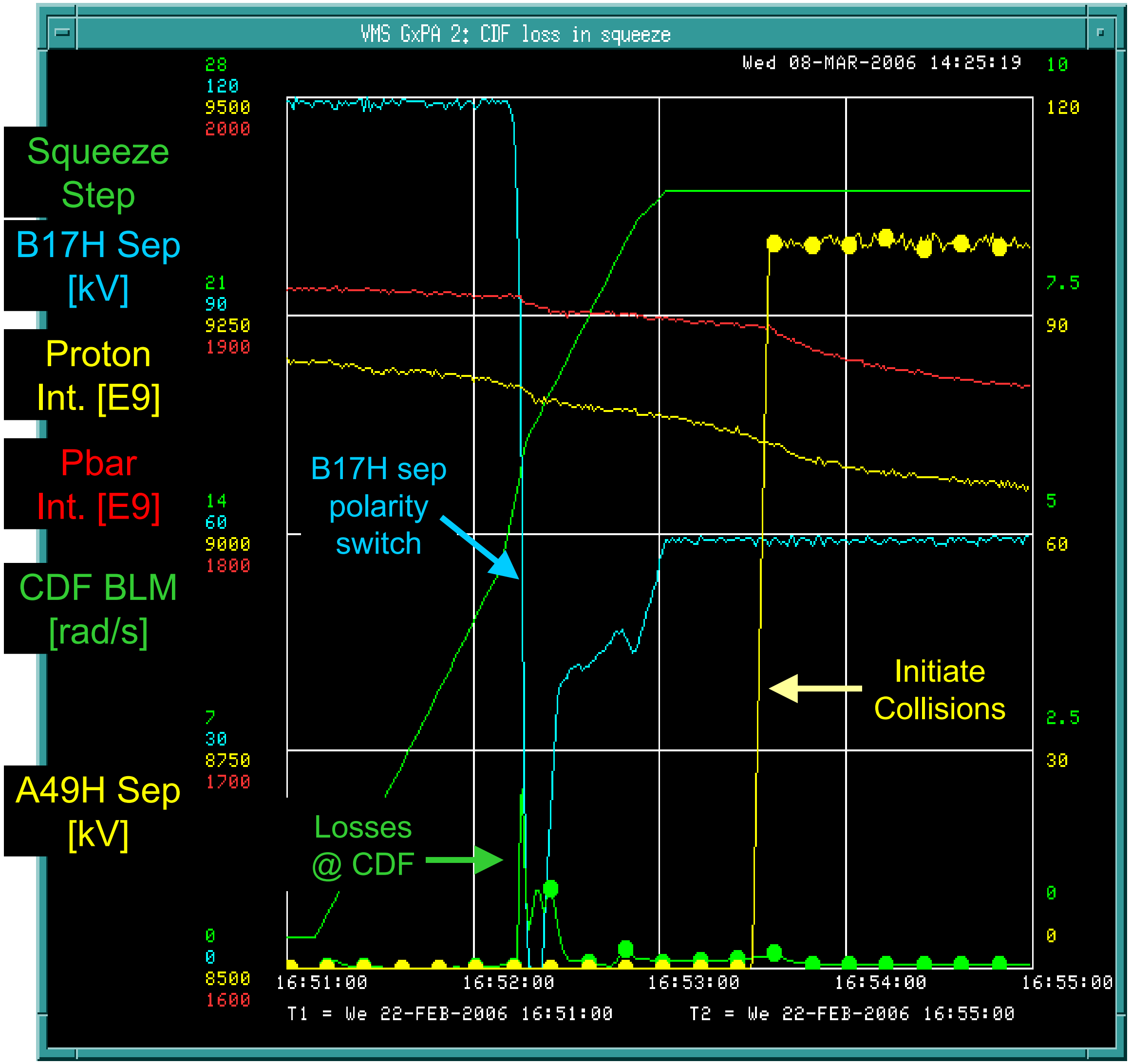

VMS GxPA 1: Horn 2 RAW
Wed 08-MAR-2006 11:24:24
Energy [GeV]
Bus Current [Amps]
Proton Int. [E9]
Pbar Int. [E9]
Proton Length [ns]
Pbar Length [ns]
1000 5000 10000 2400
750 3750 9000 2100
500 2500 8000 1800
250 1250 7000 1500
0 0 6000 1200
5 5
4 4
3 3
2 2
1 1
Artifacts of cogging
16:47:00
16:48:00
16:49:00
16:50:00
T1 = We 22-FEB-2006 16:47:00
T2 = We 22-FEB-2006 16:51:00

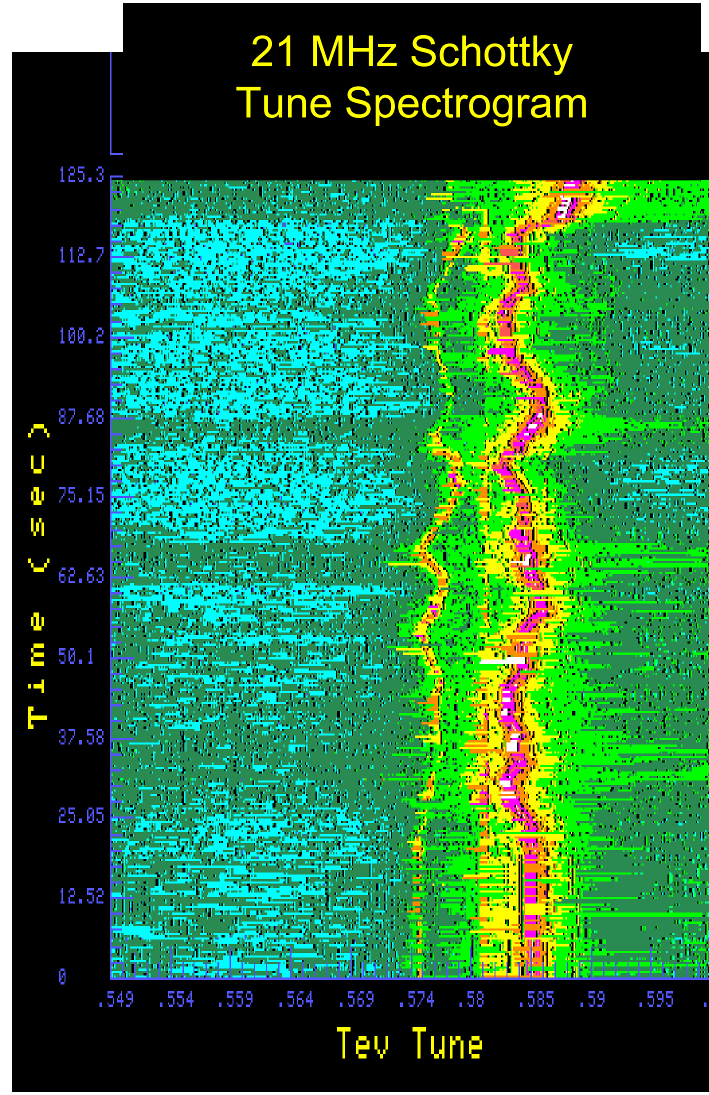

21 MHz Schottky
Tune Spectrogram
Time (sec)
125.3
112.7
100.2
87.68
75.15
62.63
50.1
37.58
25.05
12.52
0
.549 .554 .559 .564 .569 .574 .58 .585 .59 .595
Tev Tune

Ramp Inefficiencies

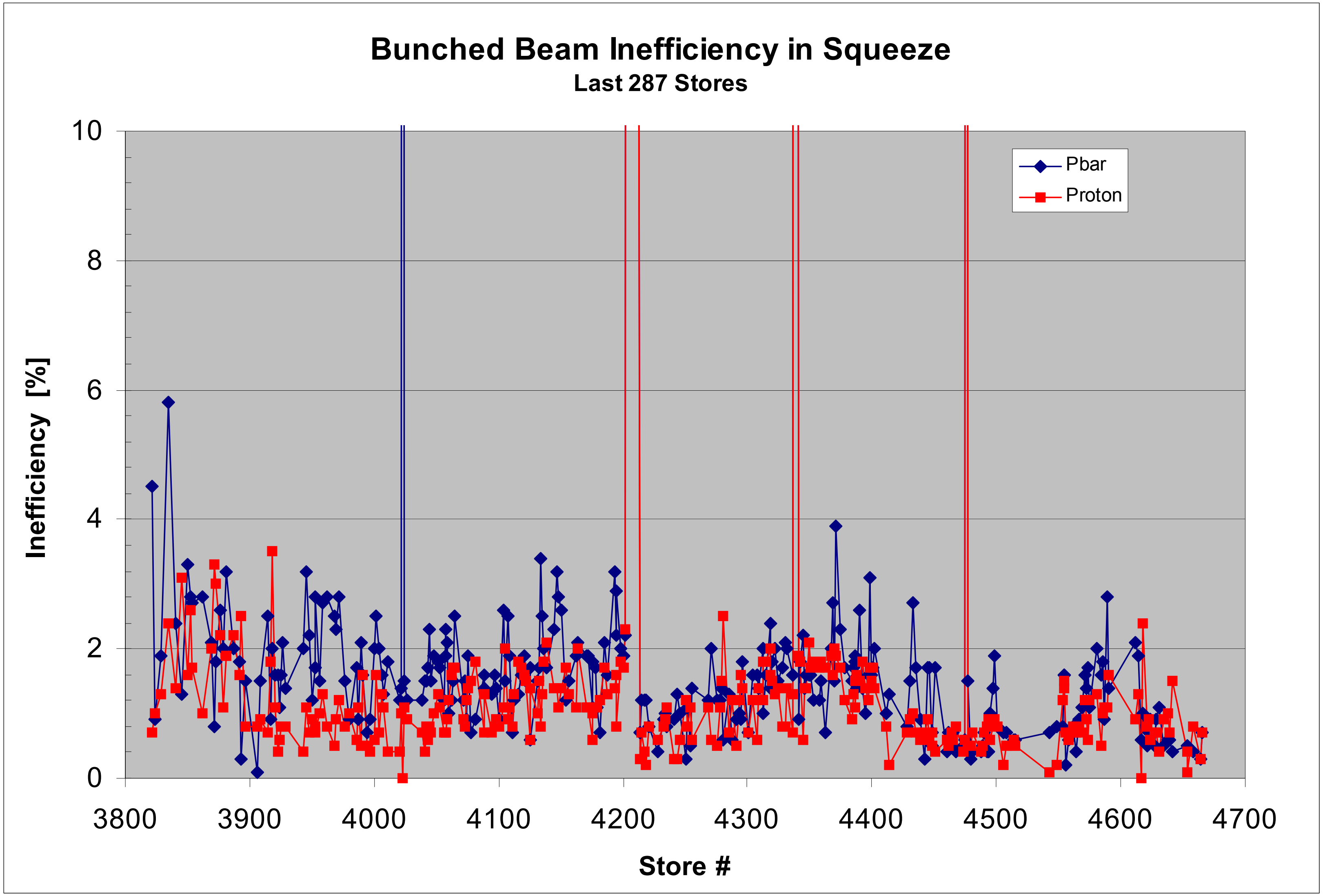


Through the Squeeze

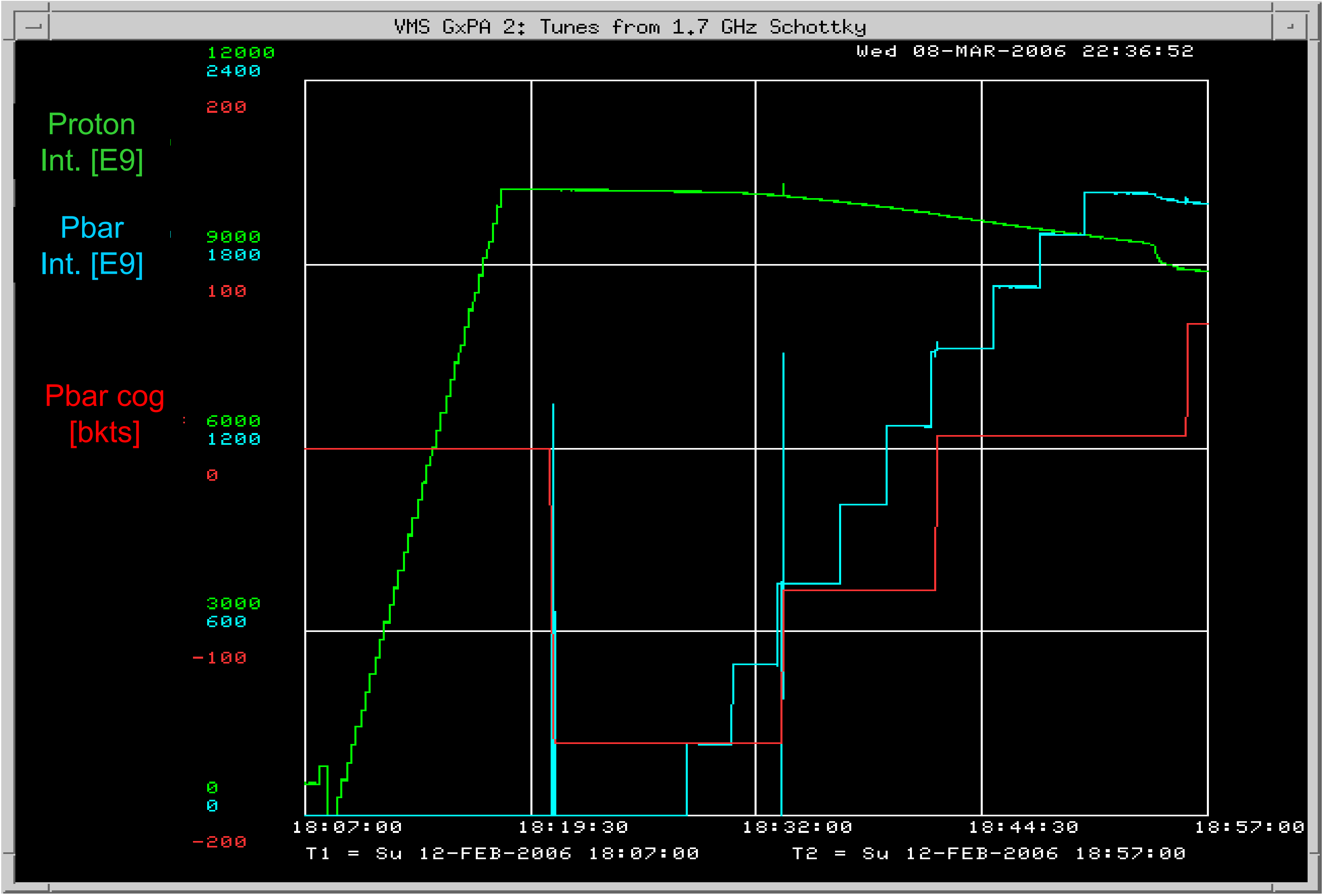


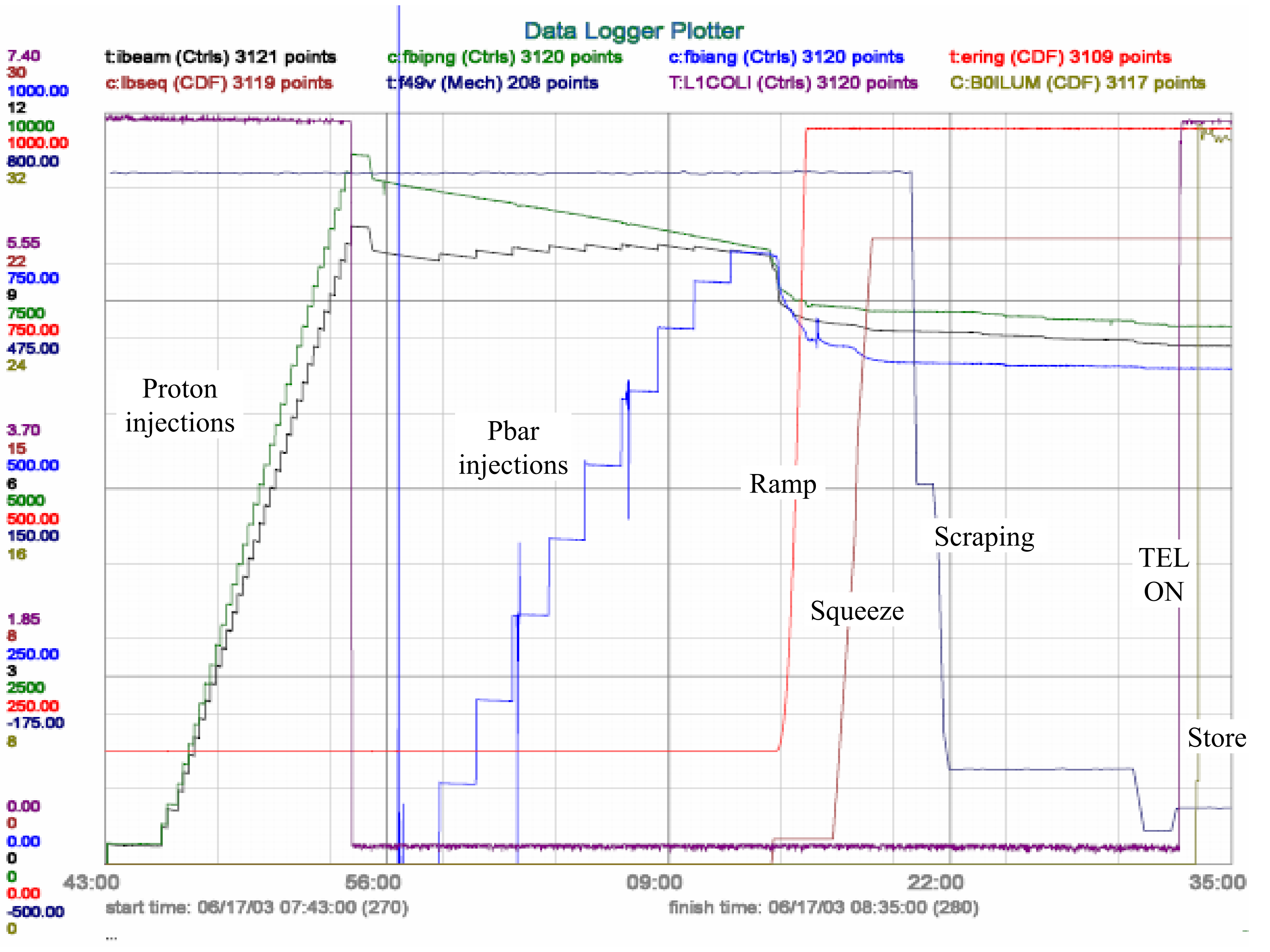


Squeeze Inefficiencies

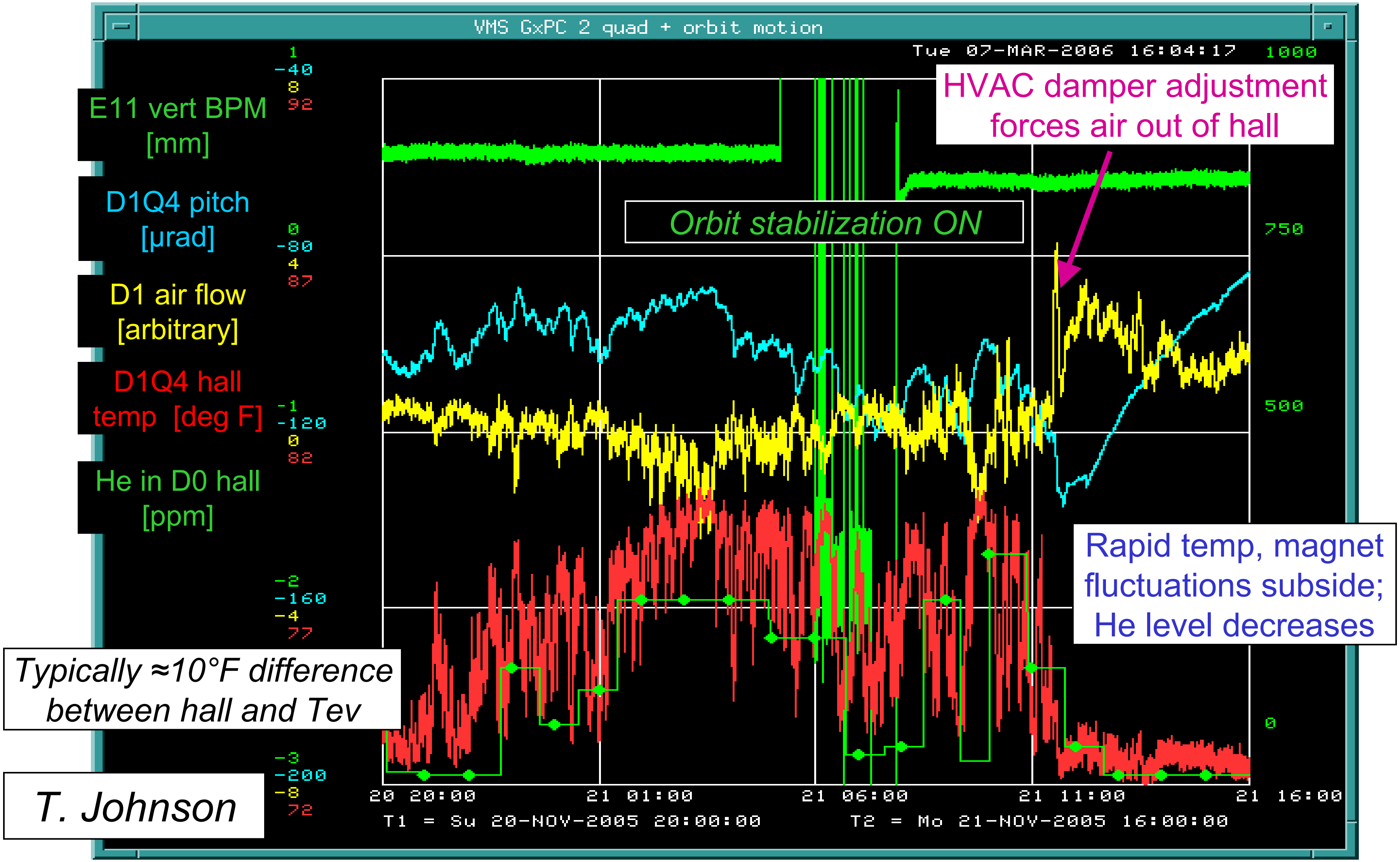


Comfort Plot @ 150 GeV




Data Logger Plotter
t:ibeam (Ctrls) 3121 points
c:fbipng (Ctrls) 3120 points
c:fbiang (Ctrls) 3120 points
t:ering (CDF) 3109 points
c:lbseq (CDF) 3119 points
t:f49v (Mech) 208 points
T:L1COLI (Ctrls) 3120 points
C:B0ILUM (CDF) 3117 points
7.40
30
1000.00
12
10000
1000.00
800.00
32
5.55
22
750.00
9
7500
750.00
475.00
24
3.70
15
500.00
6
5000
500.00
150.00
16
1.85
8
250.00
3
2500
250.00
-175.00
8
0.00
0
0.00
0
0
0.00
-500.00
0
43:00
56:00
09:00
22:00
35:00
start time: 06/17/03 07:43:00 (270)
finish time: 06/17/03 08:35:00 (280)
Proton injections
Pbar injections
Ramp
Squeeze
Scraping
TEL ON
Store

Quad Motion Depends on Hall / Tevatron Differential Pressure



Recent Component Failures

- Nov 21 – B17 spool package
  - B11 horz separator spark caused multi-house quench
  - Kautzky valve on spool failed closed

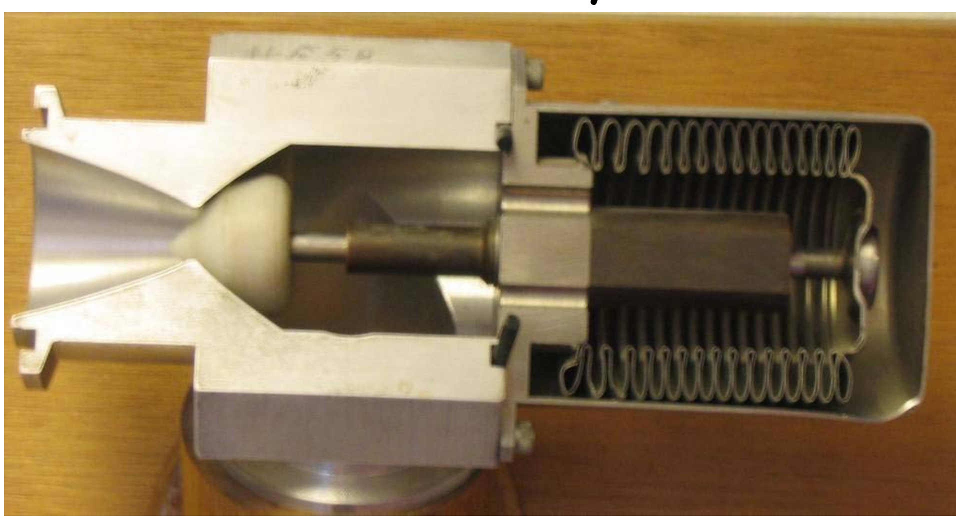
- Jan 24 – Insulating vacuum leak in A44
  - Operator error – left SQD0 (skew coupling) supply off
  - Tunes landed badly after initiating collisions, large losses
  - A44 cell not hit with losses, quenched with adjacent cells
  - Faulty O-ring installation years ago finally failed

- Feb 22 – F47-2 dipole
  - Spare abort input pulled abort spuriously
  - Kautzky valve on dipole failed closed

Kautzky Valve Poppets

- During quench, pressure forces valve open, allows He to escape
- Poppet can break off, remain in closed position
- 1 similar failure in 20 years, now 2 in three months
  - Replace all ≈1200 He Kautzky valve poppets during shutdown

Closed Kautzky valve



Broken poppet from B17 spool Kautzky valve